Induction of Through-Thickness Compressive Residual Stresses and Application to the Mitigation of the Effect of Surface Defects on the Fatigue Life of Thin Metal Plates by LSP

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5th INTERNATIONAL CONFERENCE ON LASER PEENING & RELATED PHENOMENA

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CINCINNATI, OHIO

Induction of Through-Thickness Compressive Residual Stresses and Application to the Mitigation of the Effect of Surface Defects on the Fatigue Life of Thin Metal Plates by LSP

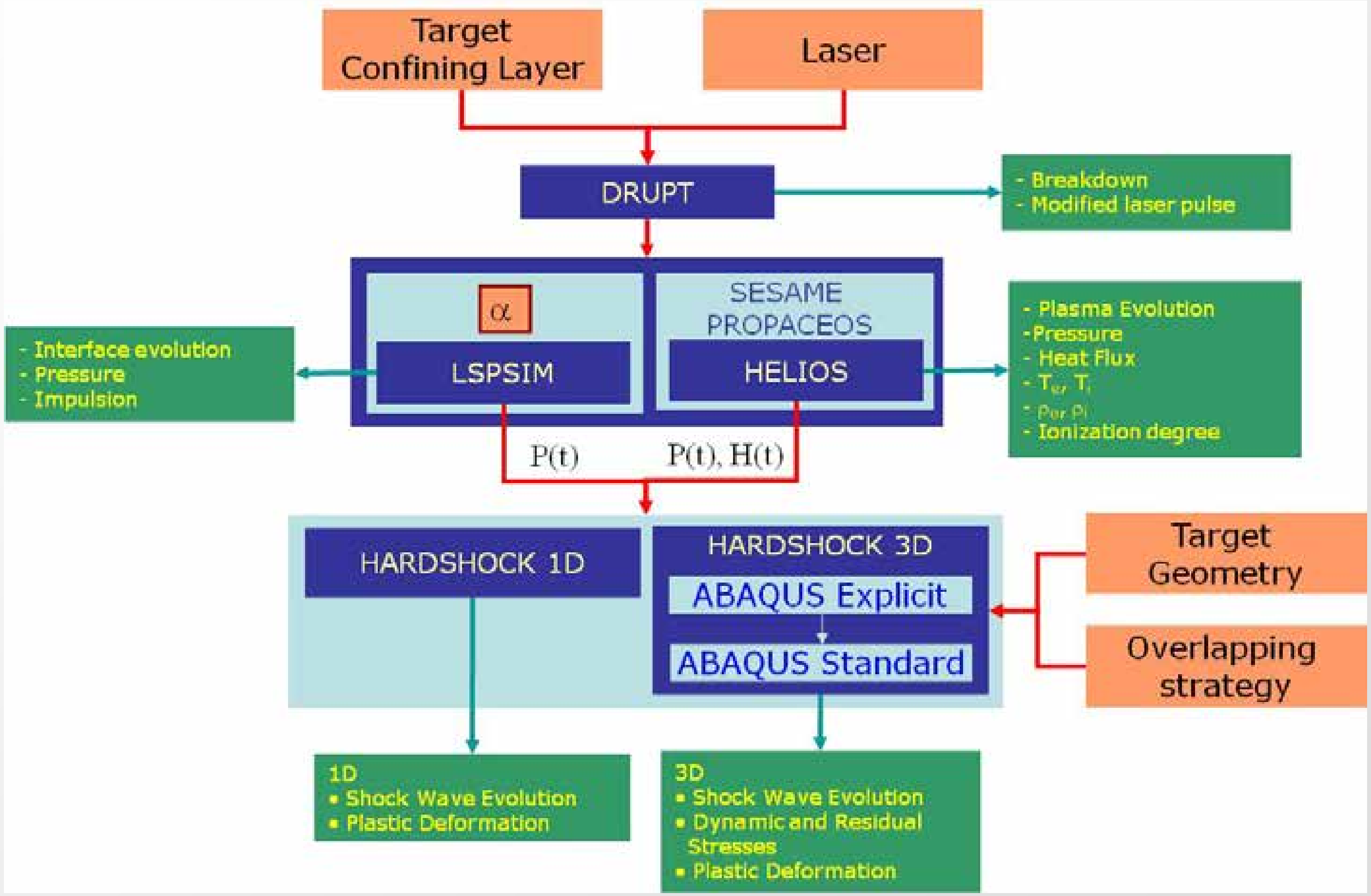
OUTLINE:

- Introduction
- Predictive Assessment Methods developed at CLUPM
- Experimental LSP Setup at CLUPM
- The Problem of Laser Shock Processing of thin metal sheets
- Engineering residual stress distribution for fatigue life enhancement
  - Induction of through-thickness compressive RS's fields in thin plates
  - Fatigue life enhancement of notched Al2024-T351 specimens
- Discussion and Outlook

INTRODUCTION

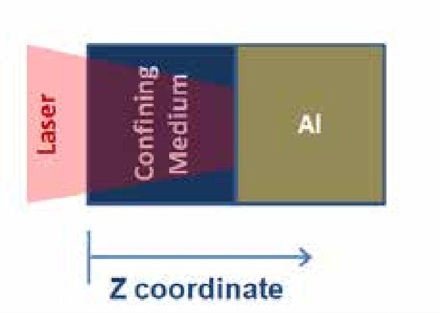
- Laser Shock Processing (LSP) is developed as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions, what makes the technique specially suitable and competitive with presently use techniques for the treatment of heavy duty components in the aeronautical, nuclear and automotive industries.
- In particular, the treatment of thin plates for, i.e., the aeronautical industry, is still a topic not fully addressed by the current industrial approaches. The desired induction of through-thickness compressive RSs fields is generally difficult to achieve due to the local + global deformations induced by high-energy-per-pulse processing systems.
- The authors have directly envisaged this problem by means of their coupled predictive + experimental methodology and have obtained successful results.
- In a combined way, the highly beneficial effect of LSP treatments has been demonstrated in the extension of life of thin Al2024-T351 test specimens with induced surface notches.

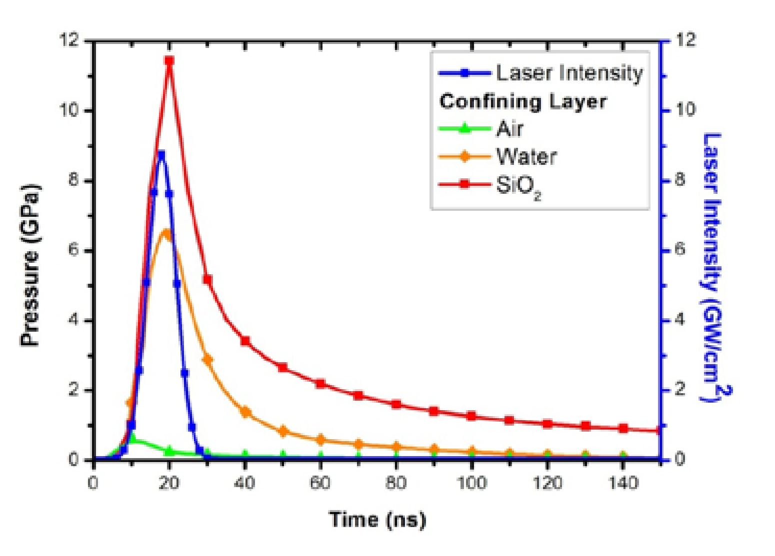
The SHOCKLAS Calculational System

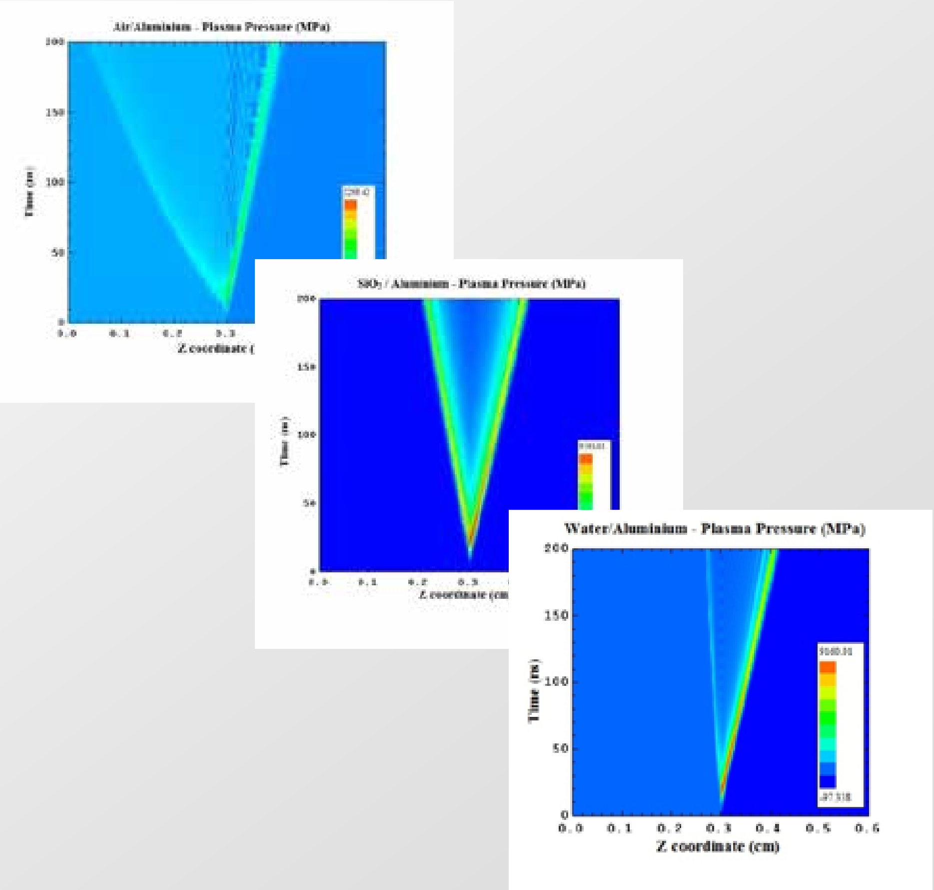


HELIOS

Analysis of relative influence of confining material



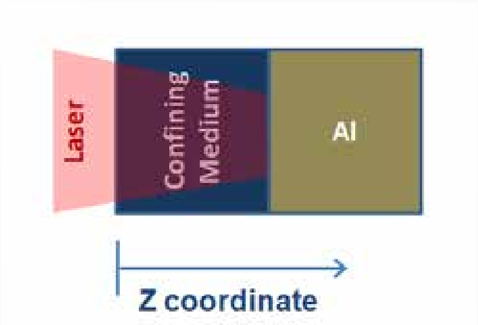


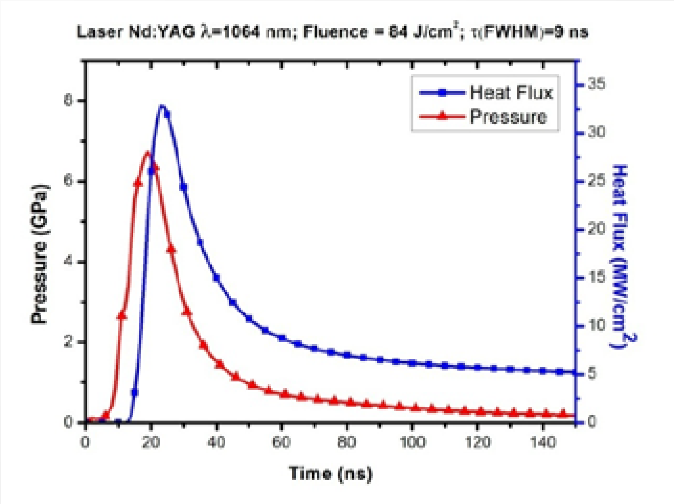


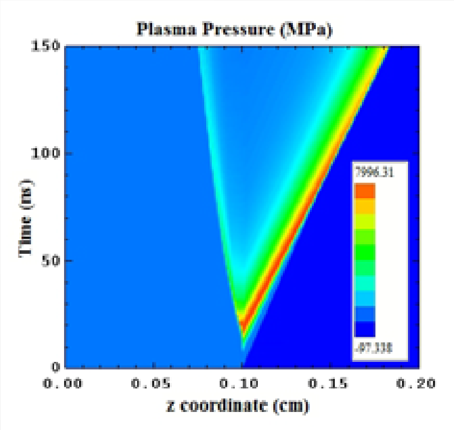
CONSISTENT MODEL FOR CONFINED PLASMA EXPANSION IN LSP

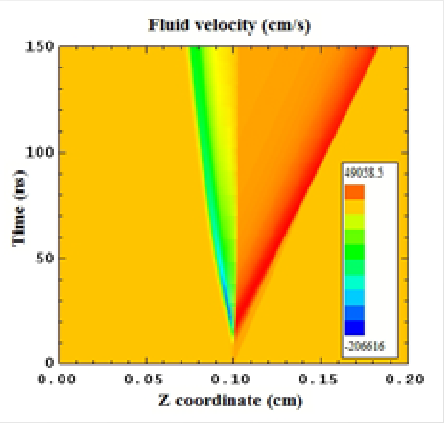
HELIOS

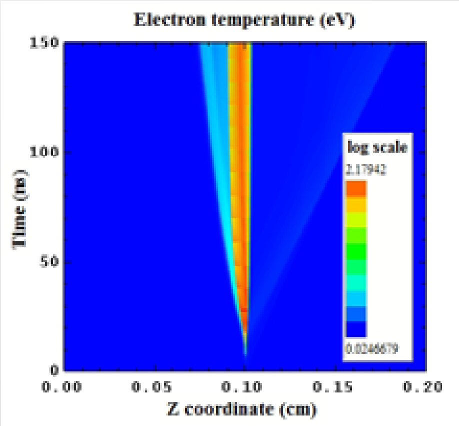
Analysis of plasma for LSP conditions

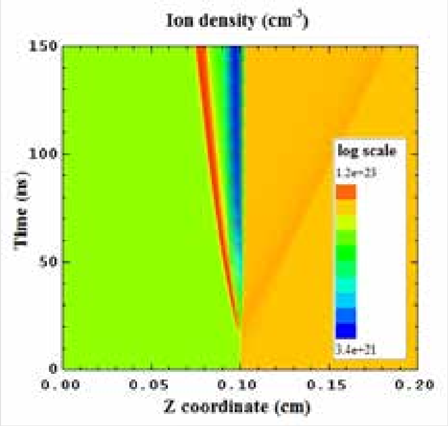




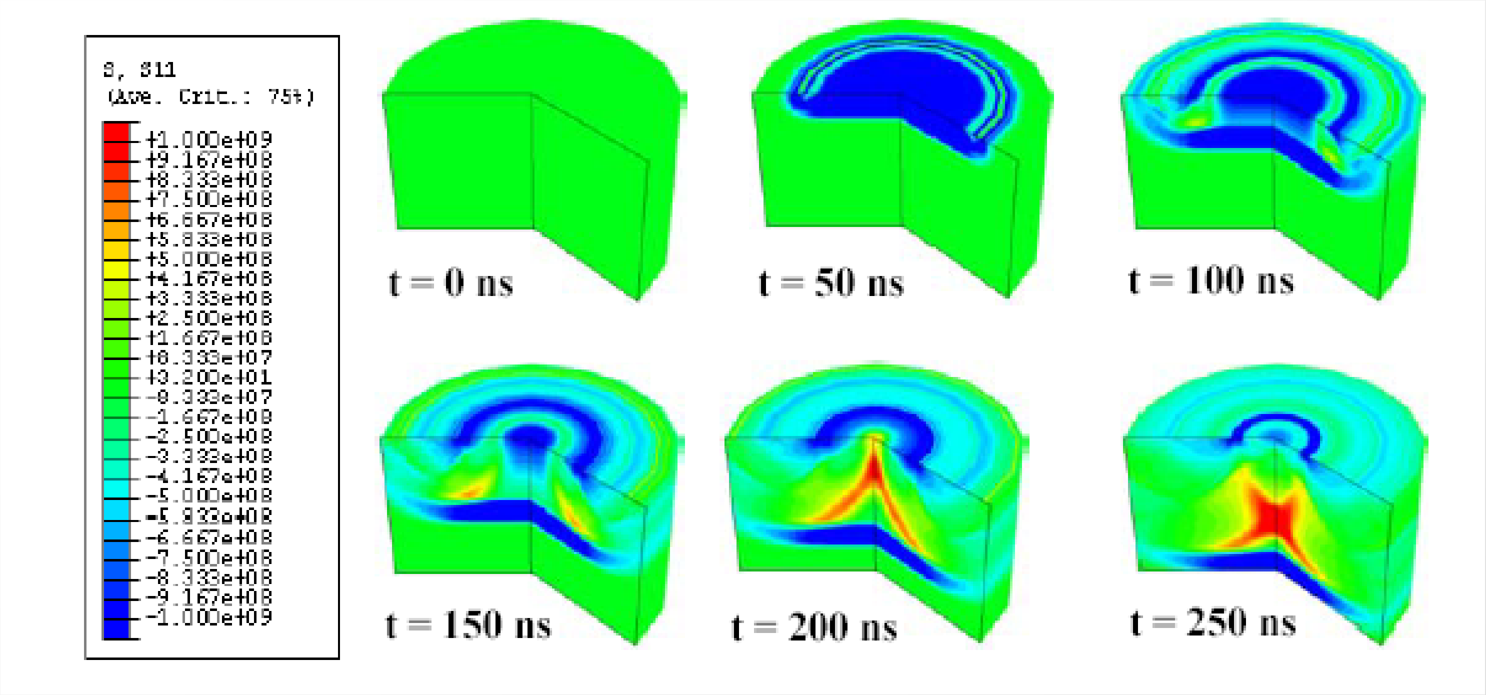








SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP



Ocaña, J.L. et al.: "Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser-shock-processed metallic alloys". Proc. SPIE 5448, 642-653 (2004)

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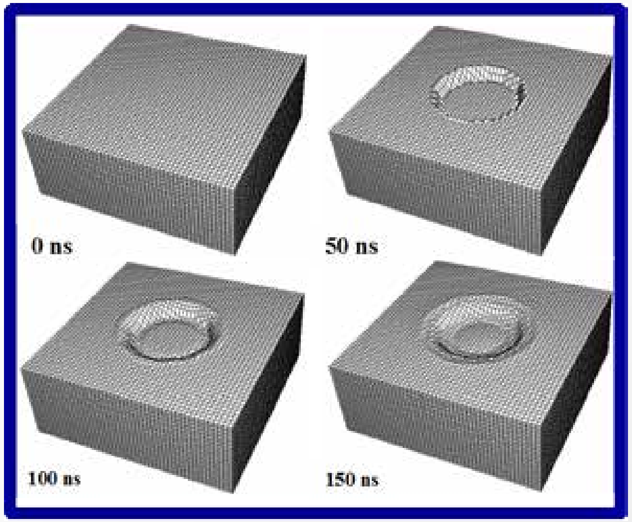
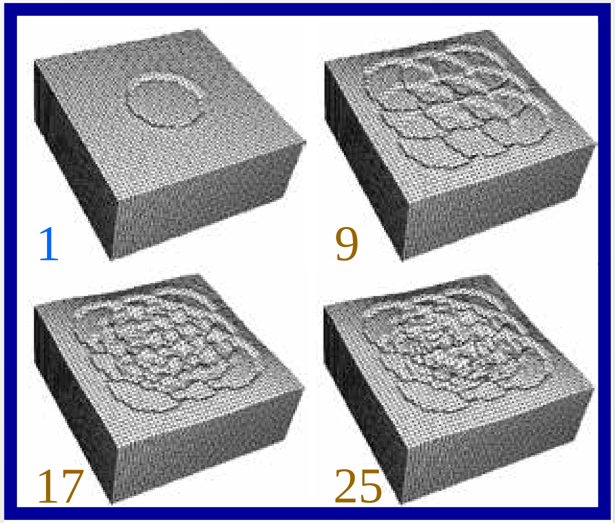
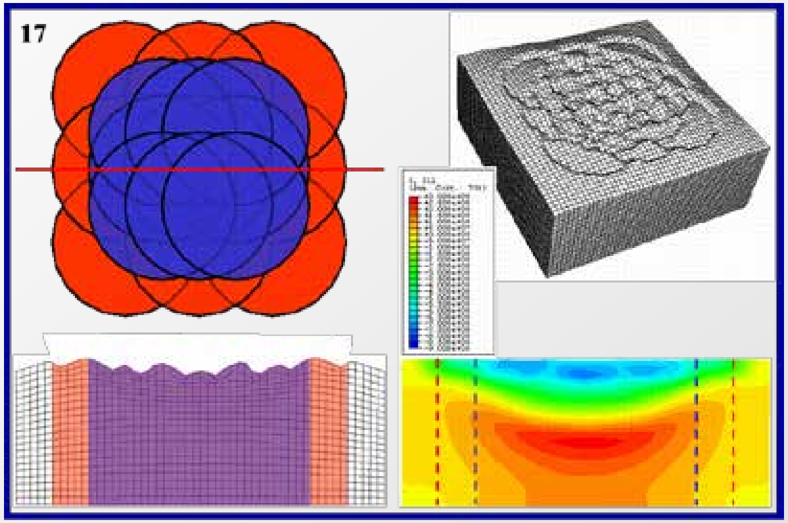
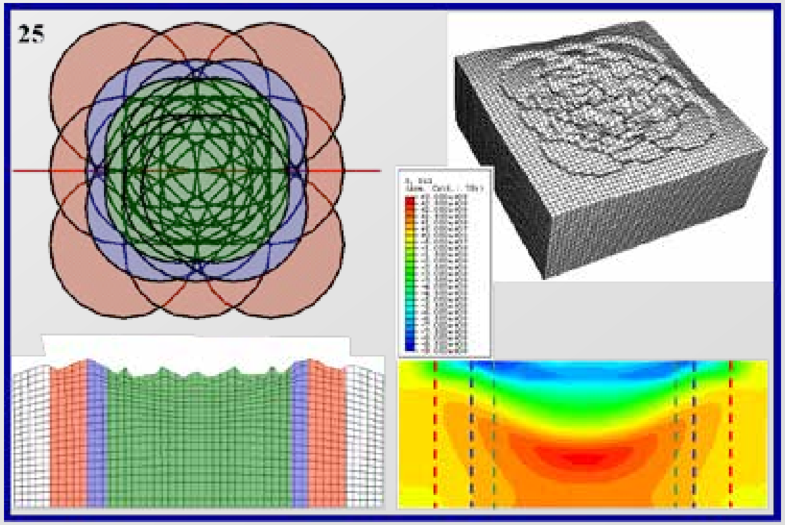
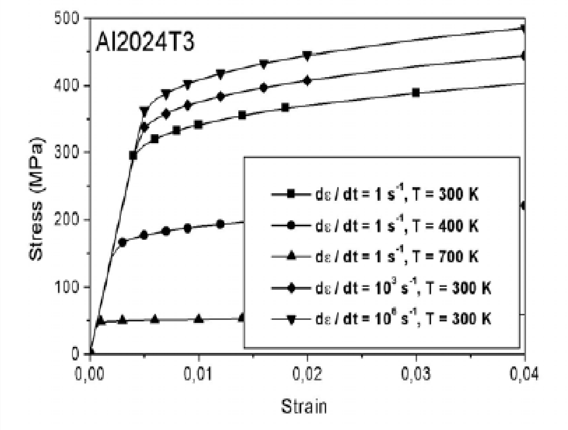


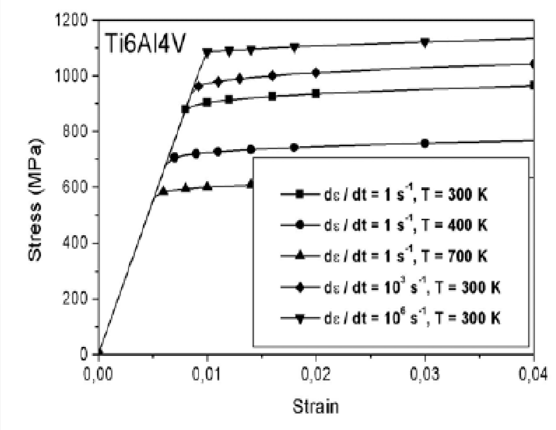


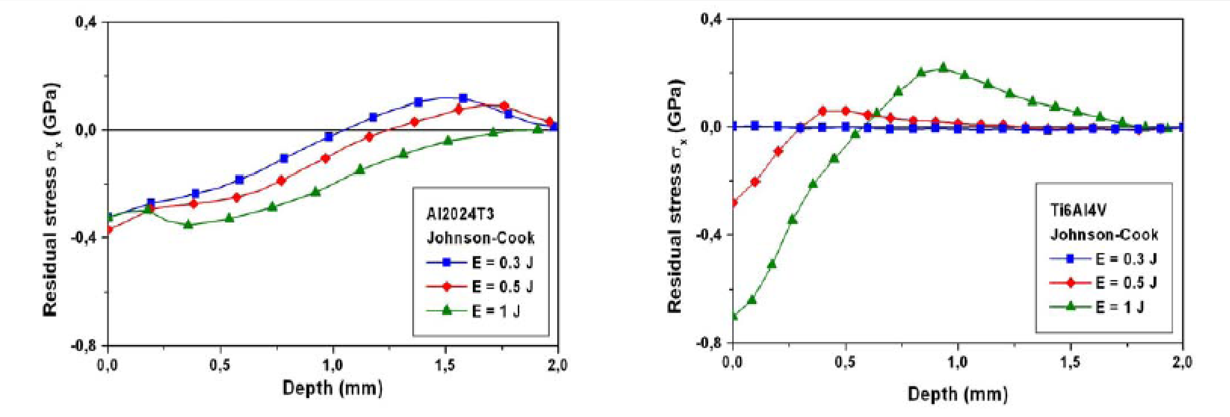




SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP







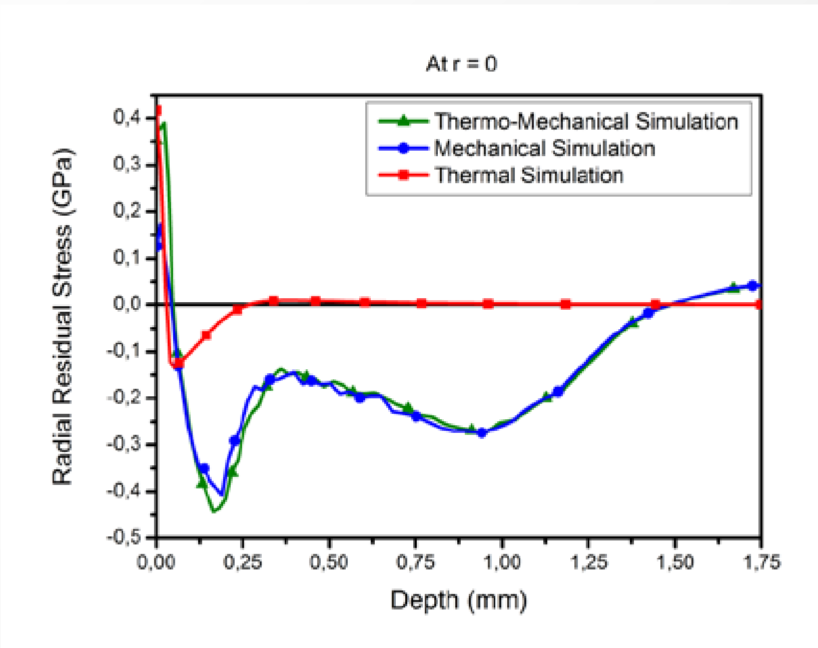
Ocaña, J.L. et al.: "Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser-shock-processed metallic alloys". Proc. SPIE 5448, 642-653 (2004)

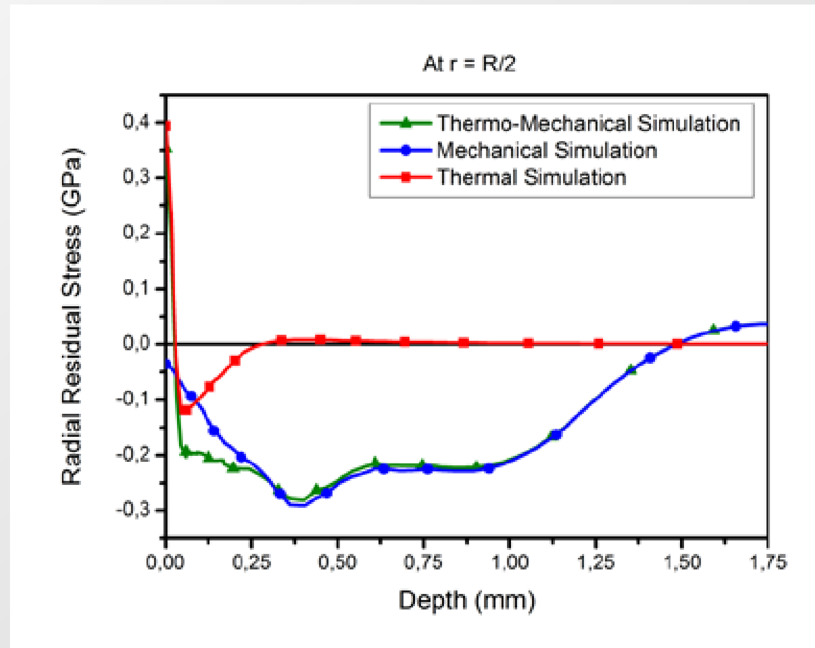
SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP

Evaluation of relative effects of thermal and mechanical waves on shocked material

Water / Aluminium; Nd:YAG (1064 nm),

t= 9 ns, F= 84 J/cm^2, radius = 1.5 mm





Morales, M. et al.: Materials Science Forum, 638-642, 2682-2687 (2010)

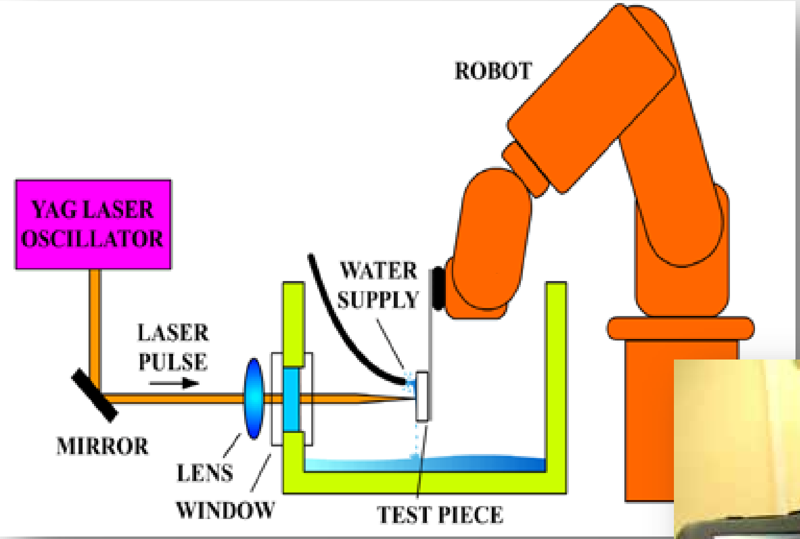
PROCESS EXPERIMENTAL SETUP

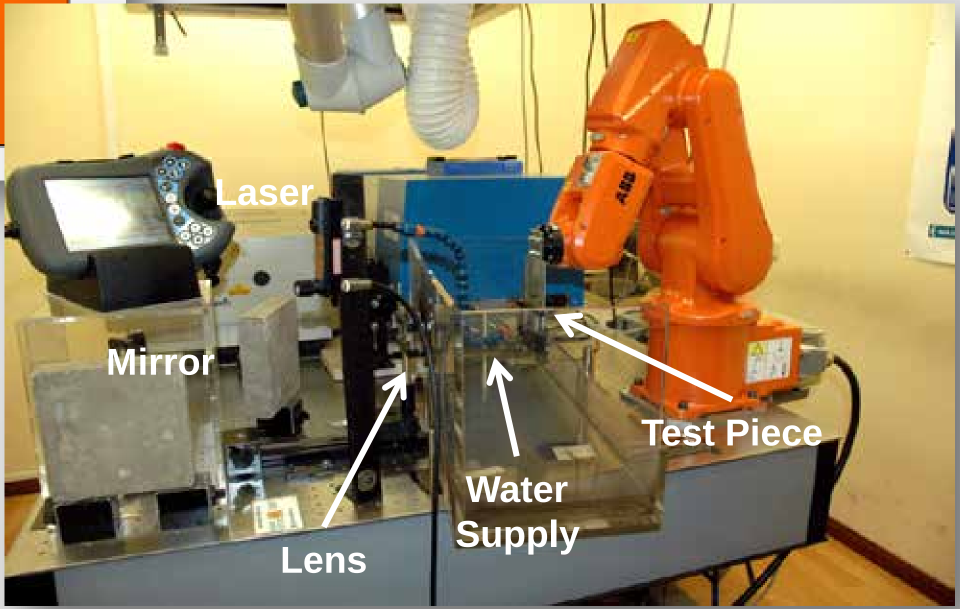
Q-SWITCHED Nd:YAG LASER

λ = 1064 nm ; E = 2,5 J/pulse
λ = 532 nm ; E = 1,4 J/pulse

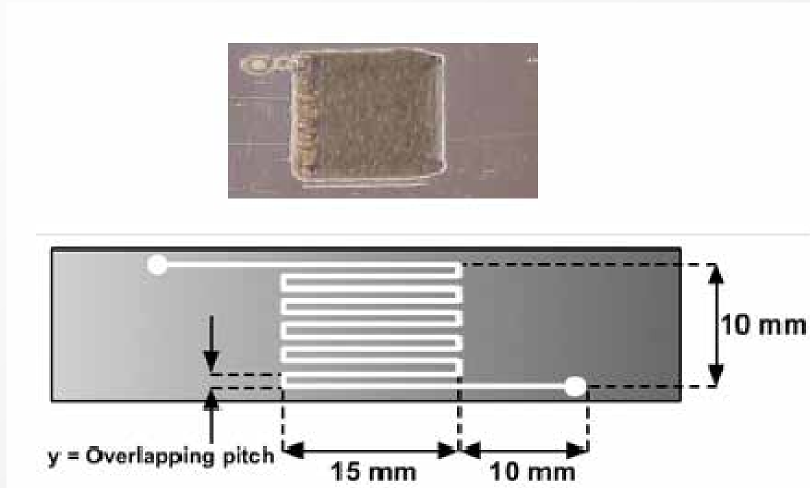
t = 10 ns; f = 10 Hz

PROCESS EXPERIMENTAL SETUP





EXPERIMENTAL PROCEDURE



$$\text{Equivalent Overlapping Density} \equiv EOD = \frac{N^{o}\text{ of pulses}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\,\frac{y}{\Delta y}}{\Delta s} = \frac{\frac{x}{d}\,\frac{y}{d}}{xy} = \frac{1}{d^{2}}$$

$$\text{Equivalent Energy Density} \equiv EED = \frac{N^{o}\text{ of pulses} \times \text{Pulse Energy}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\,\frac{y}{\Delta y}}{\Delta s}E = \frac{\frac{x}{d}\,\frac{y}{d}}{xy}E = \frac{E}{d^{2}}$$

$$\text{Equivalent local overlapping factor} \equiv ELOF = \frac{N^{o}\text{ of pulses} \times \text{Pulse Area}}{\text{Total treated surface}} = \frac{\frac{\pi}{4}\phi^{2}}{d^{2}} = \frac{\pi}{4}\left(\frac{\phi}{d}\right)^{2}$$

EXPERIMENTAL PROCEDURE

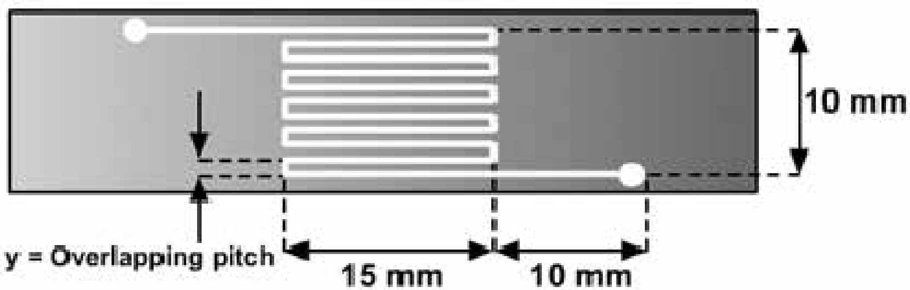
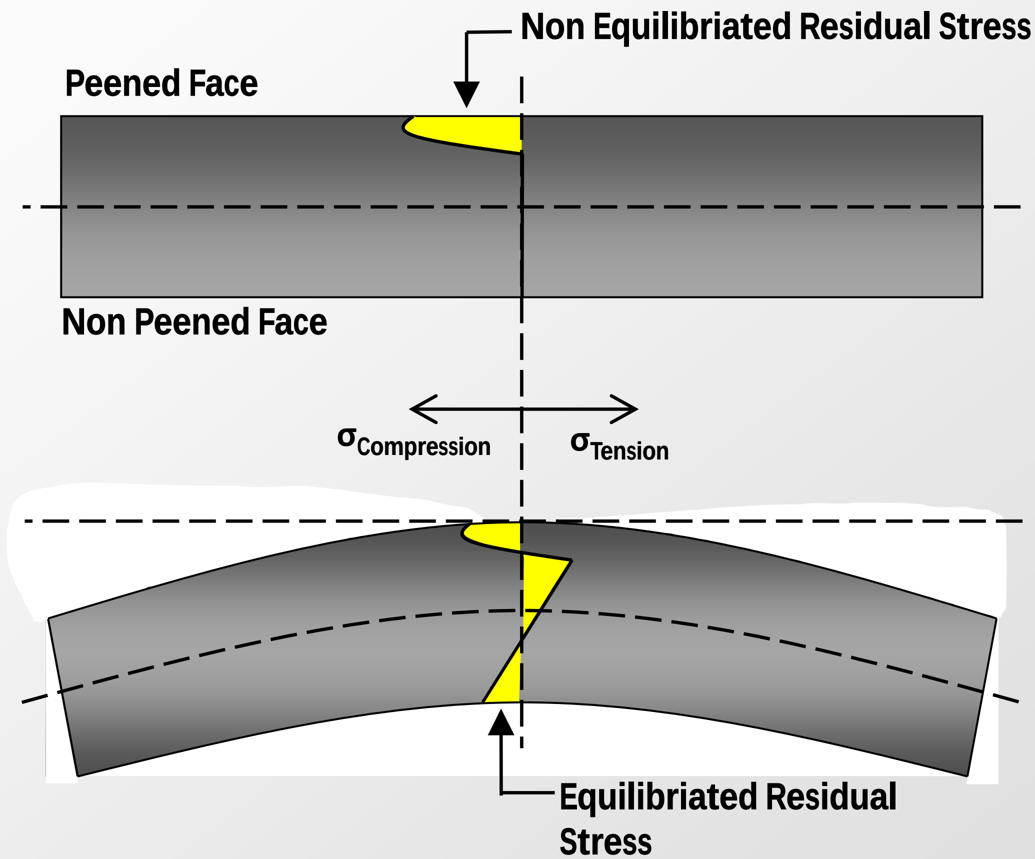


Table I: Relation between overlapping pitch and equivalent number of pulses per unit surface corresponding to the defined sweeping procedure.

Overlapping pitch Y (mm)	Equivalent overlapping density (pulses/cm^2)
0.588	289
0,33	900
0.285	1225
0.2	2500
0,141	5000

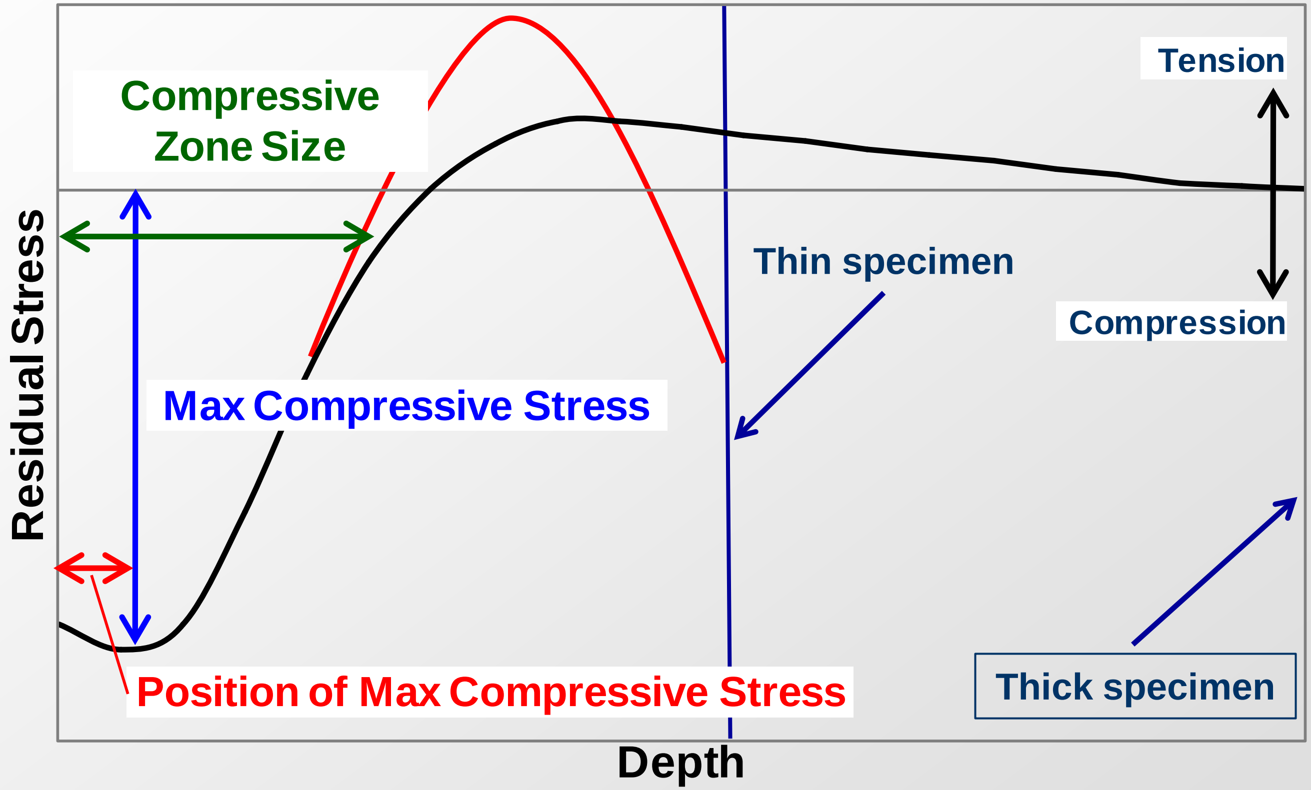
RS’s induced deformation for global workpiece stress reequilibration



N. Smyth & Prof. P. E. Irving (CU, UK)

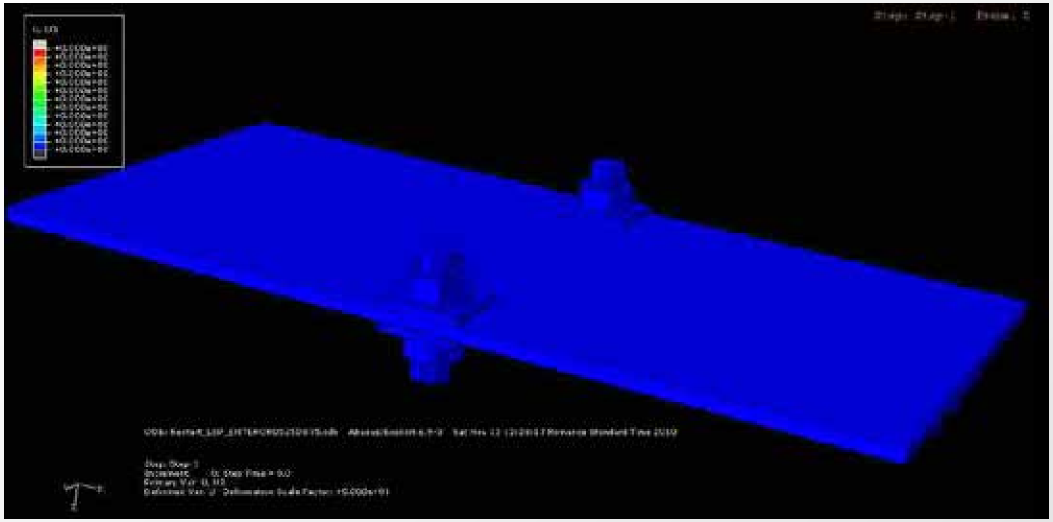
THE PROBLEM OF LASER SHOCK PROCESSING OF THIN METAL SHEETS

Key variables in the design of RS's fields distribution for improved mechanical surface properties. The special case for thin specimens

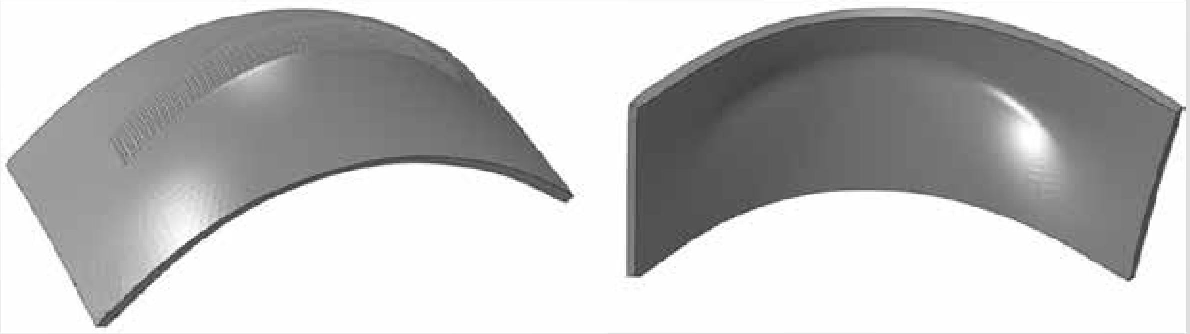


Adapted from original viewgraph from N. Smyth & Prof. P. E. Irving (CU, UK)

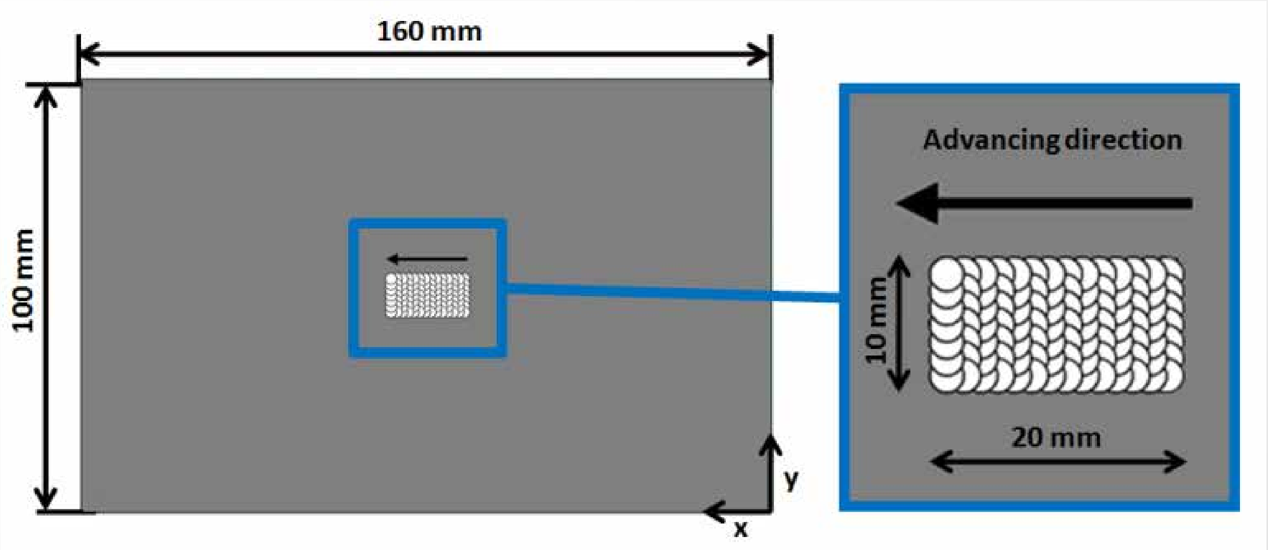
THE PROBLEM OF LASER SHOCK PROCESSING OF THIN METAL SHEETS



Local + Global Deformation (x 50)

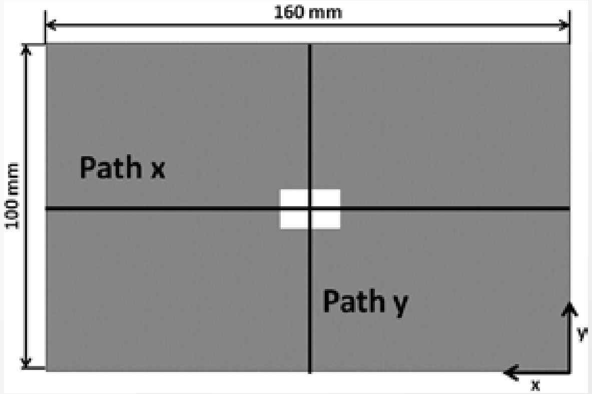


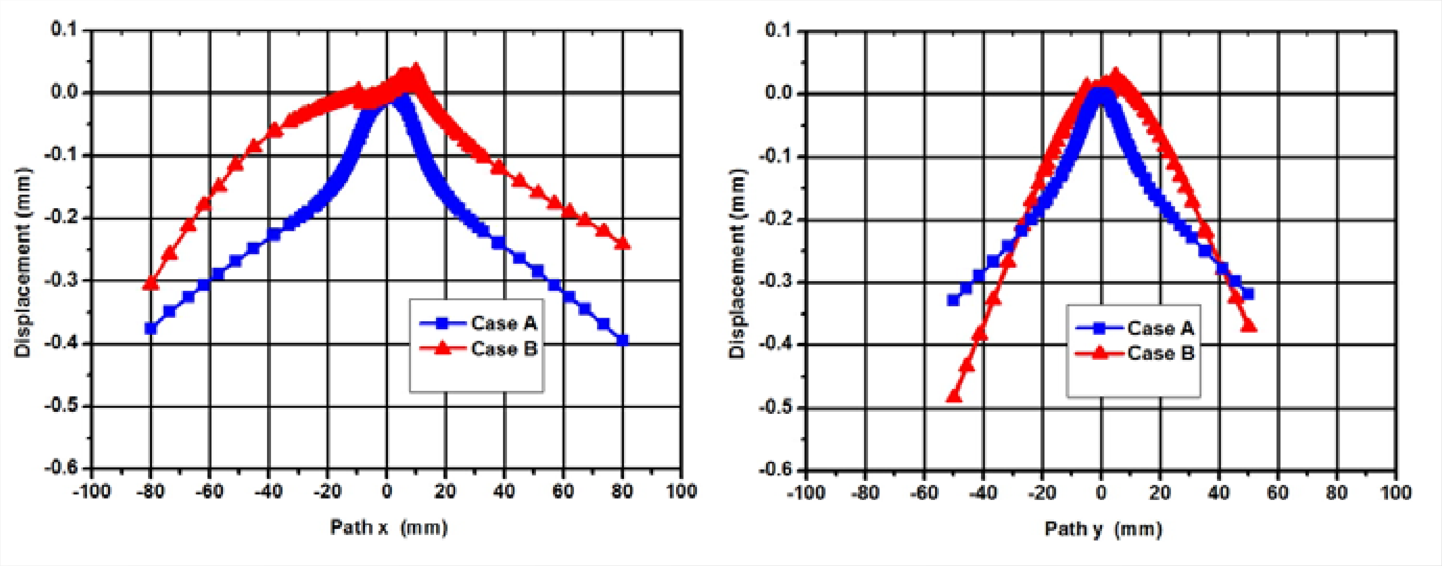
INDUCTION OF THROUGH-THICKNESS COMPRESSIVE RSs FIELDS IN THIN PLATES



Treatment condition	Laser pulse energy, E (J)	Laser pulse overlapping distance, d (mm)	Laser spot diameter, Ø (mm)	Equivalent Overlapping Density, EOD (1/cm^2)	Equivalent Energy Density, EED (J/cm^2)	Equivalent Overlapping Factor, ELOF (-)
A	2.4	0.75	1.50	178	427	3,14
B	2.4	0.75	2.50	178	427	8.73

INDUCTION OF THROUGH-THICKNESS COMPRESSIVE RSs FIELDS IN THIN PLATES





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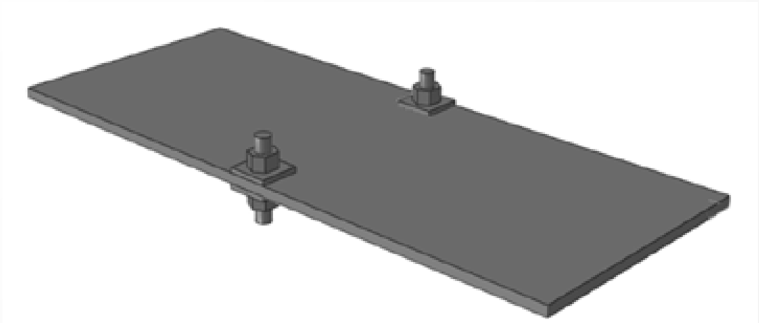
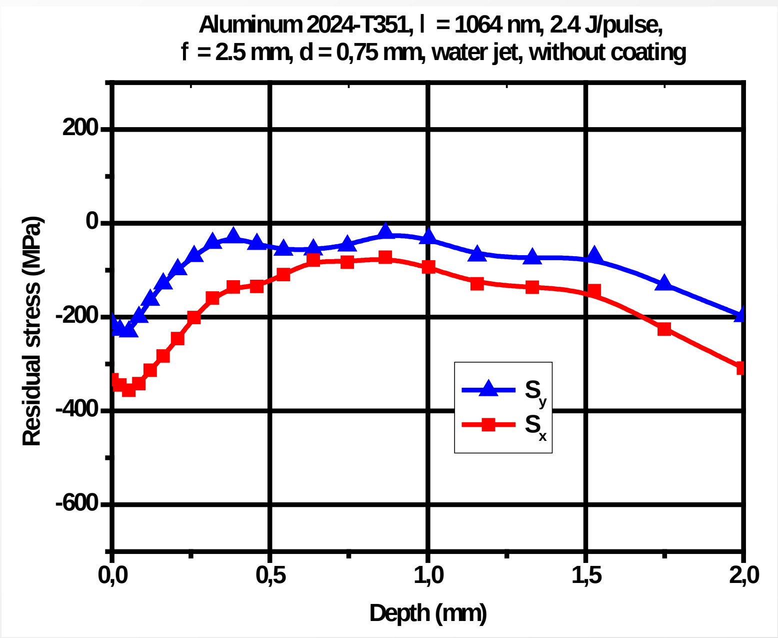
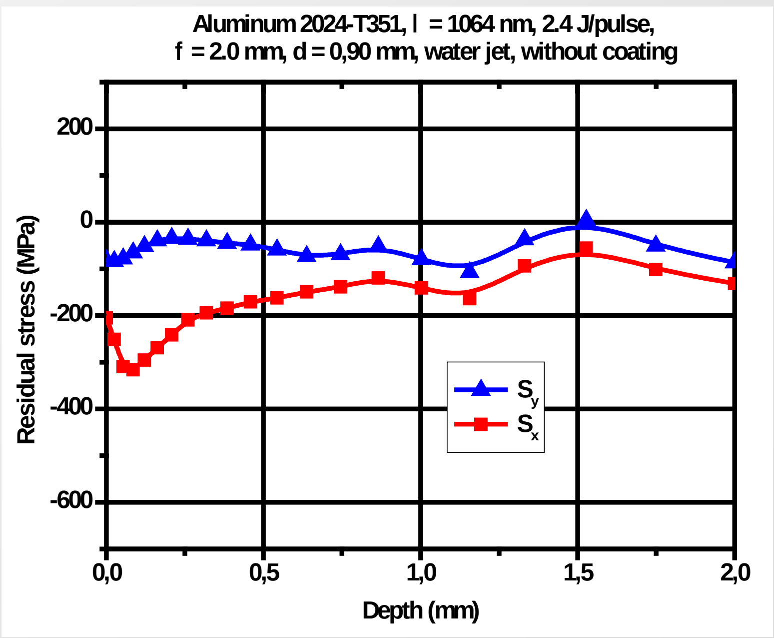


Treatment condition	Laser pulse overlapping distance, d (mm)	Laser spot diameter, Ø (mm)
B	0.75	2.50





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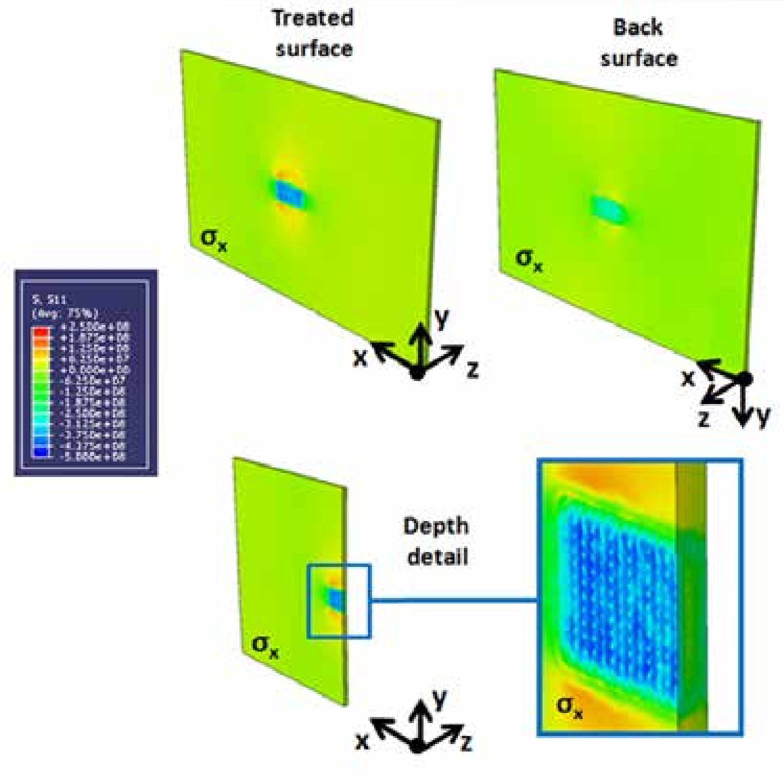

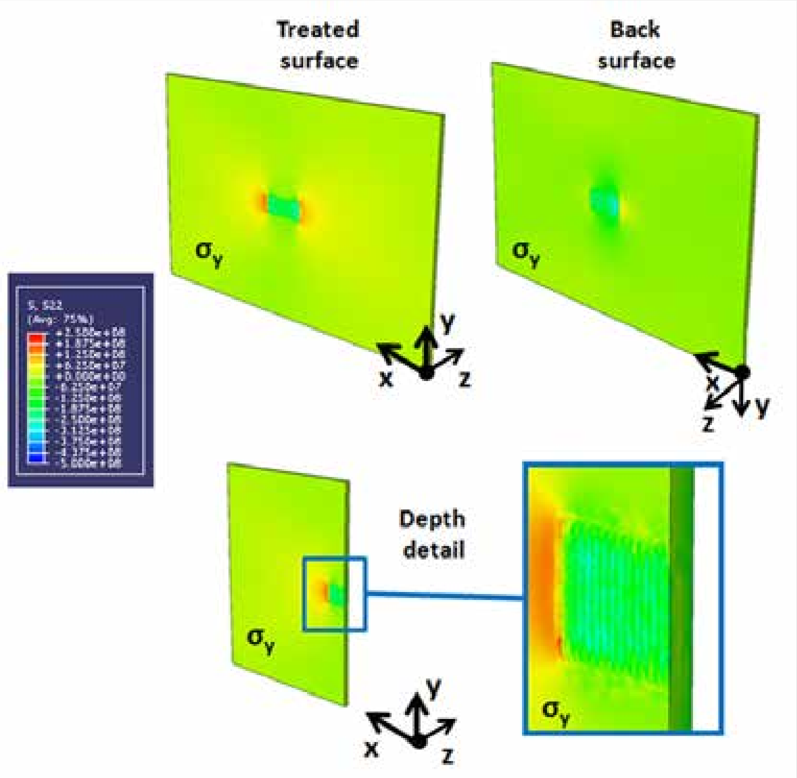

OCAÑA, J.L. et al.: Journal of Materials Processing Technology 223, 8-15 (2015)

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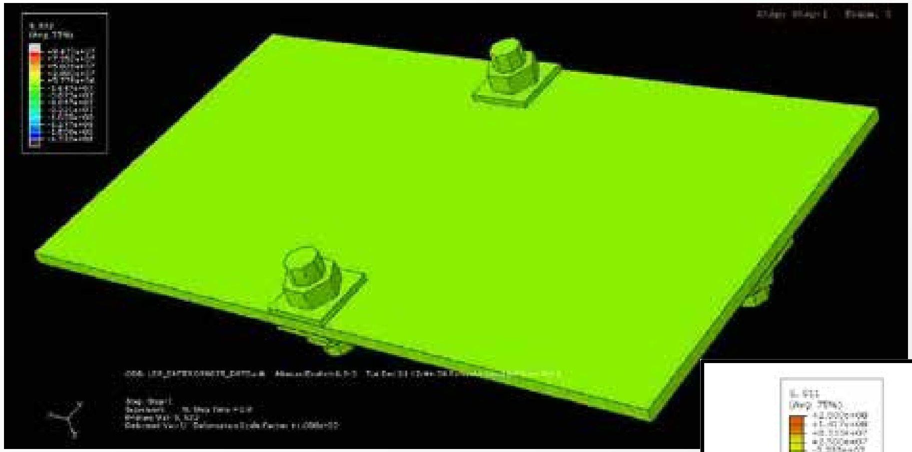

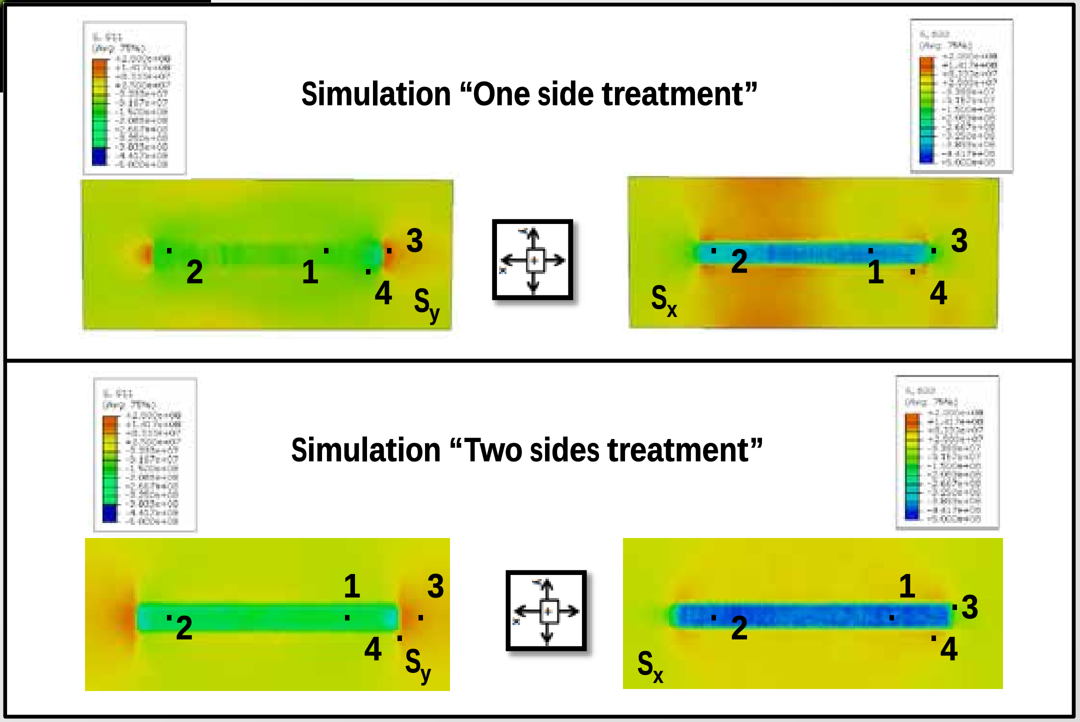

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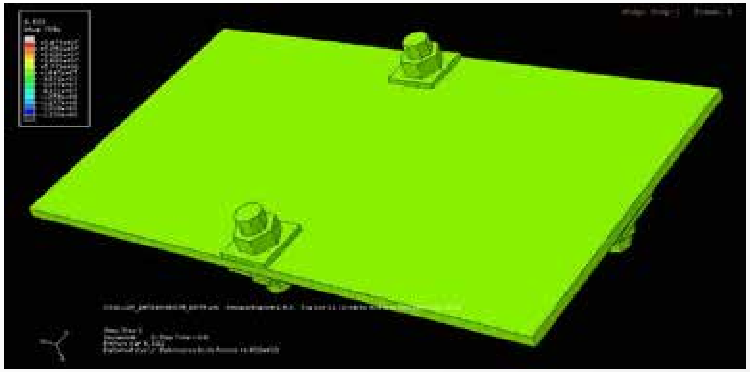
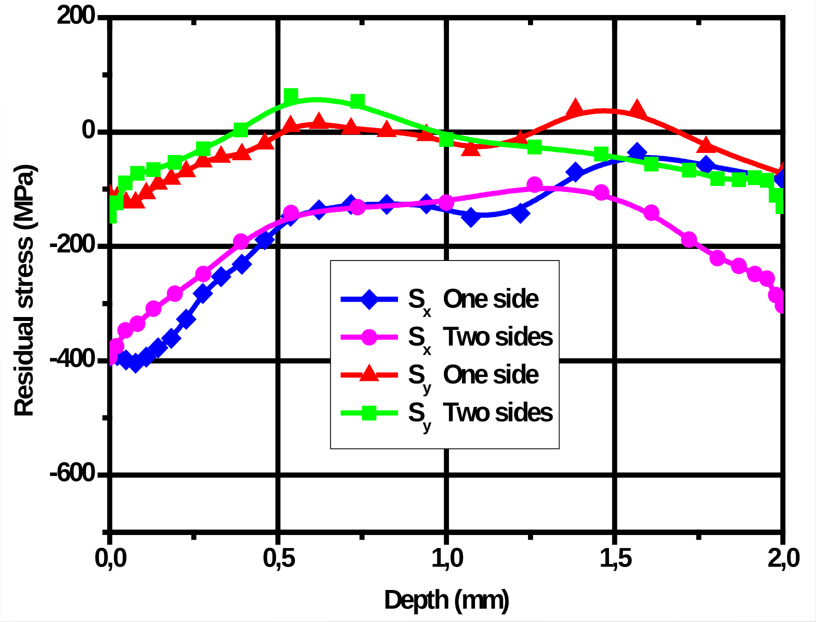
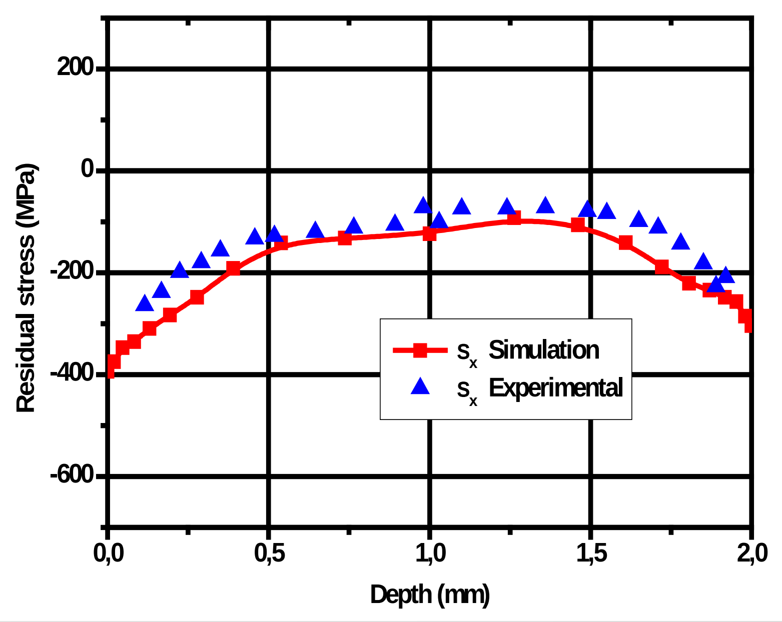
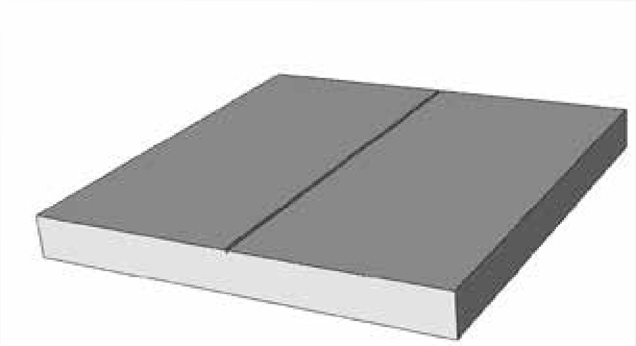
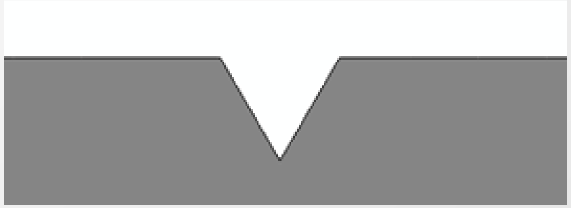




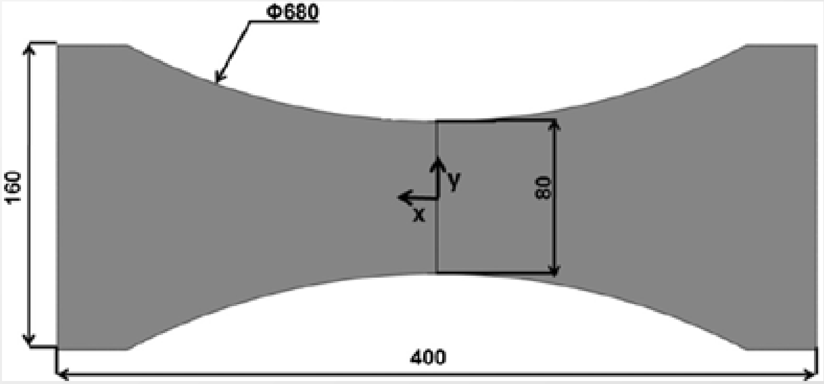


FATIGUE LIFE ENHANCEMENT OF NOTCHED AL2024-T351 SPECIMENS

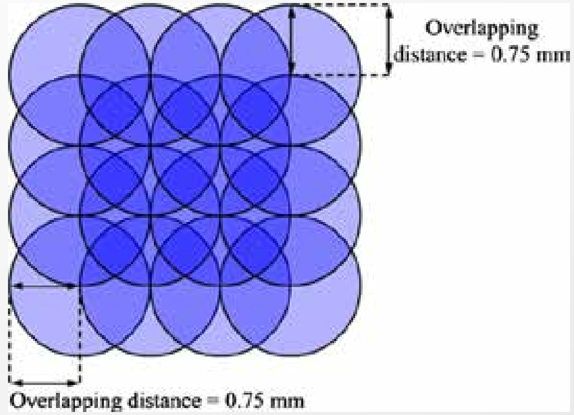


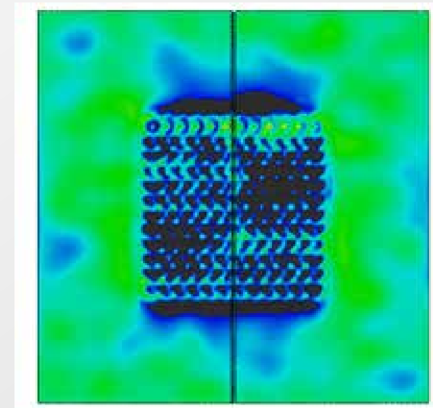


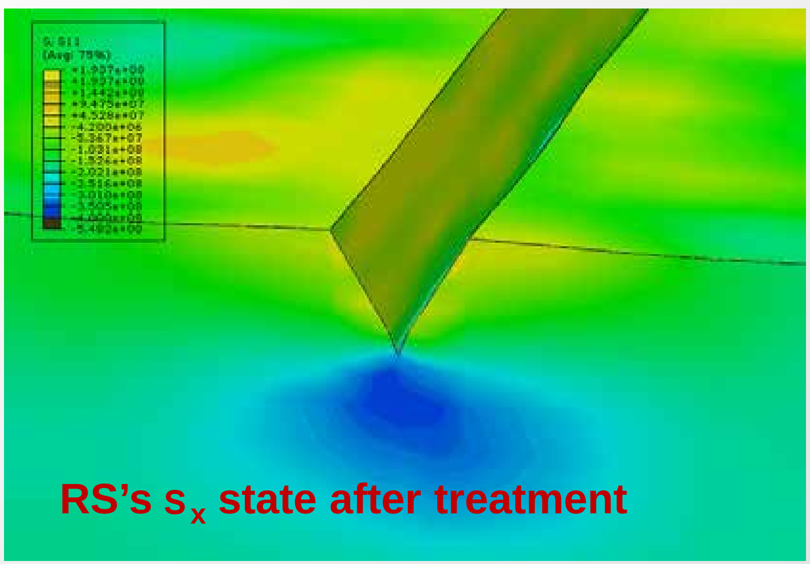
Notch: 150 mm depth, 60º angle

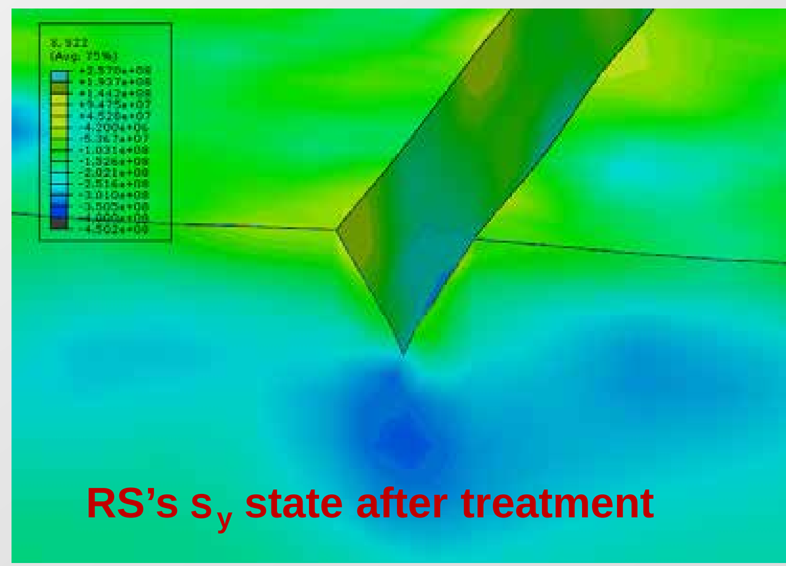


APPLICATION TO THE FATIGUE LIFE ENHANCEMENT OF NOTCHED AL2024-T351 SPECIMENS









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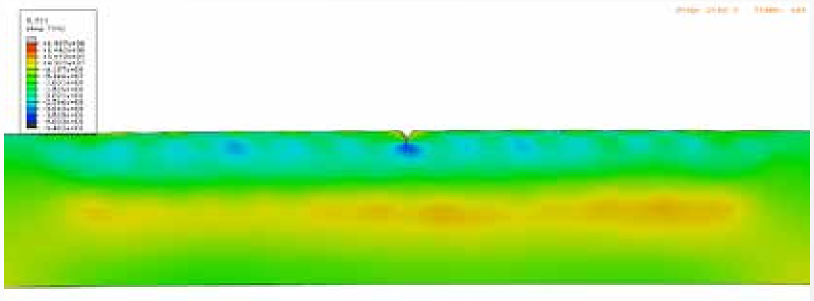
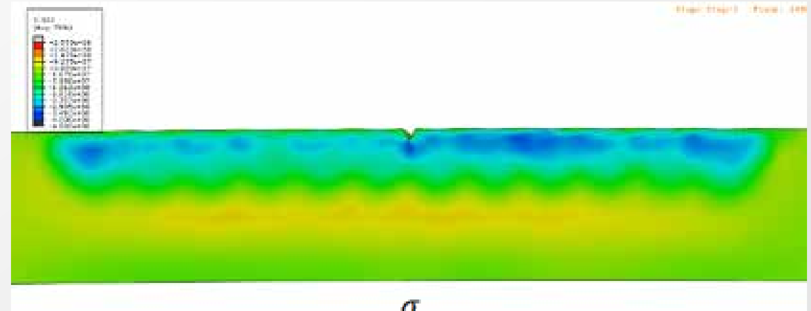
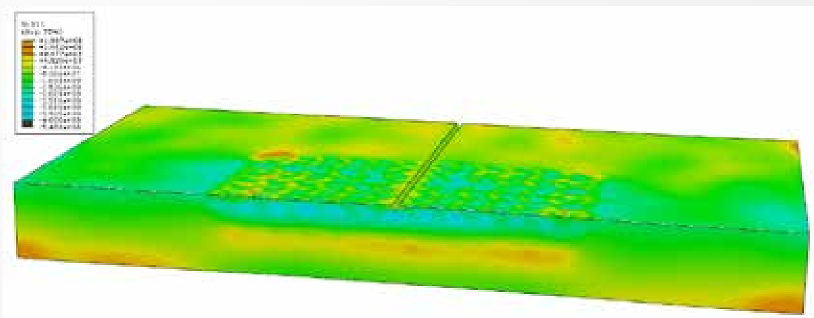


σ_x

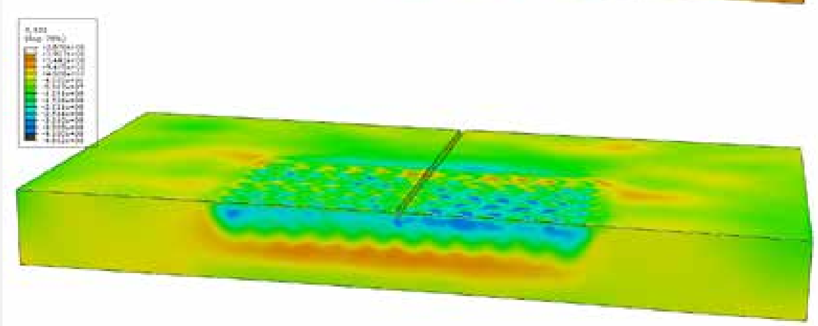


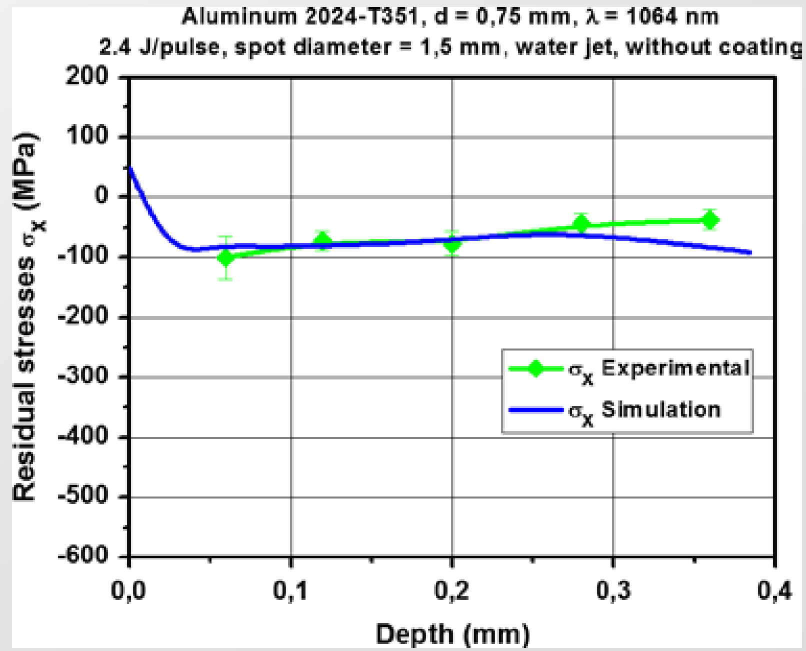
σ_y

σ_x



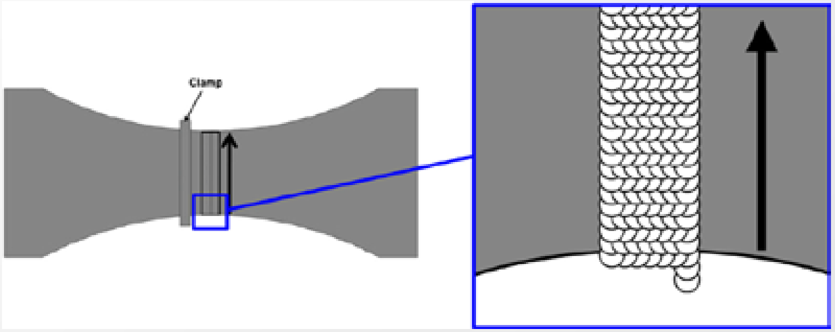
σ_y



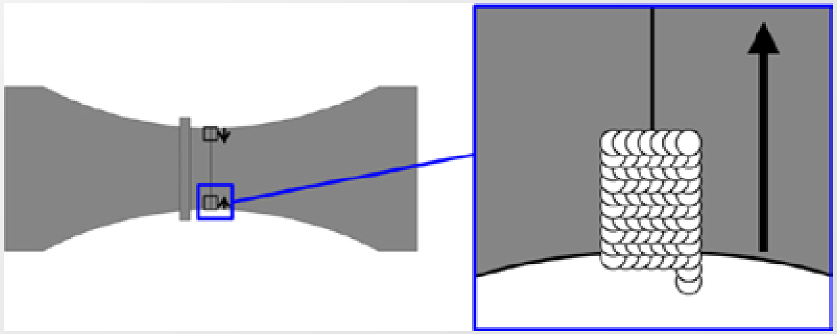


FATIGUE LIFE ENHANCEMENT OF NOTCHED AL2024-T351 SPECIMENS

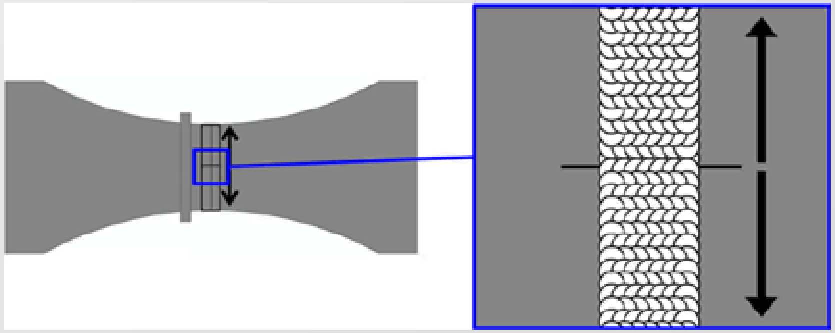
LSP Treatment Strategy 1



LSP Treatment Strategy 2

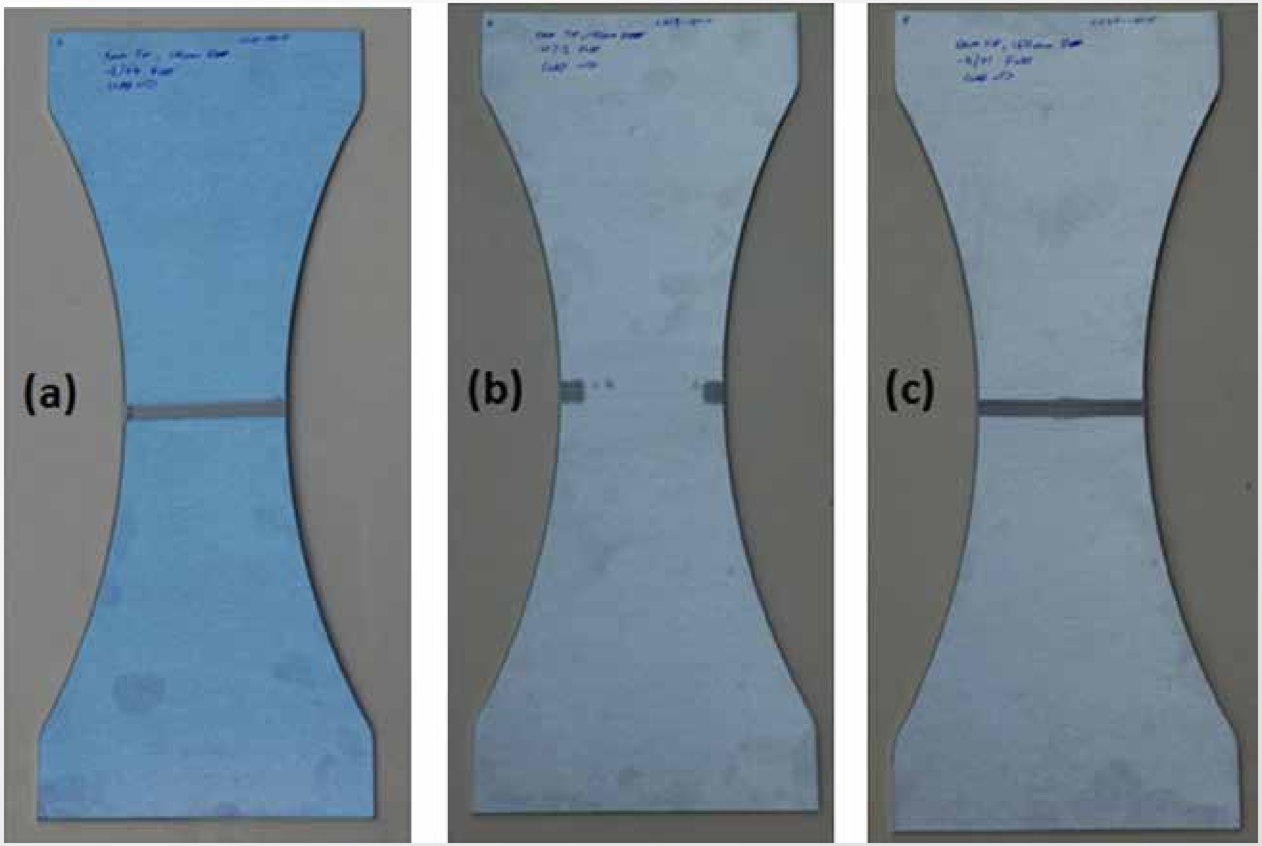


LSP Treatment Strategy 3



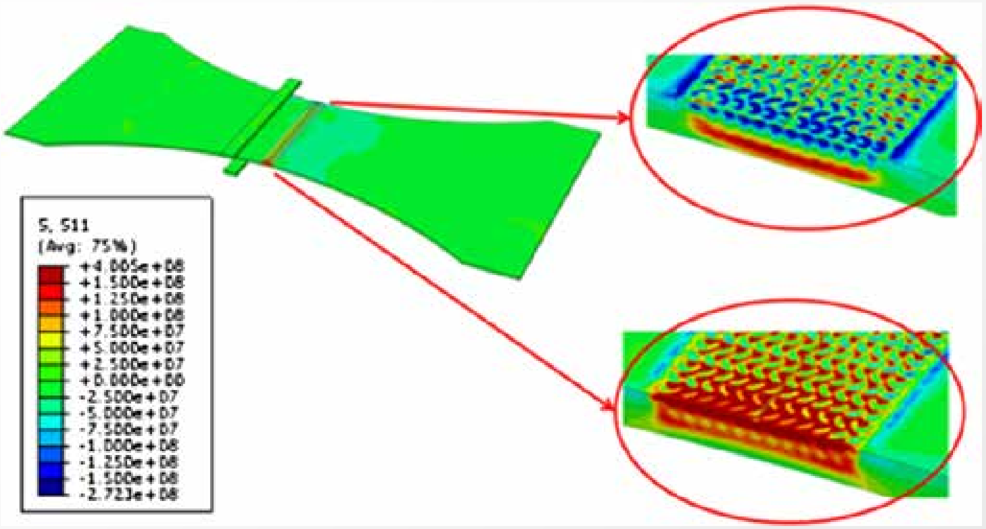
FATIGUE LIFE ENHANCEMENT OF NOTCHED AL2024-T351 SPECIMENS

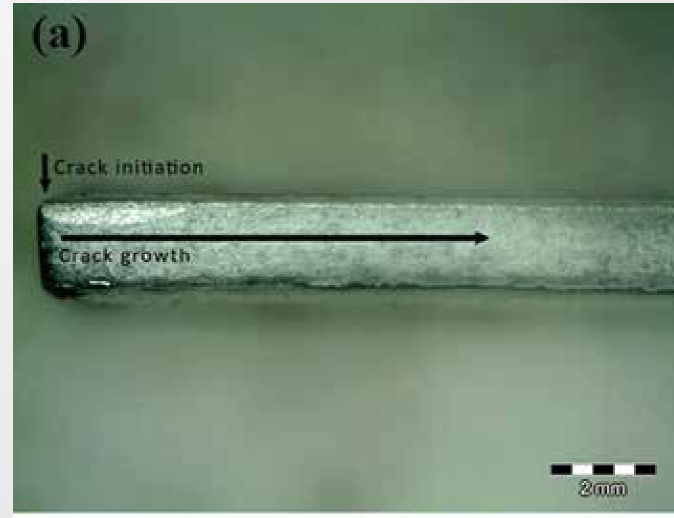
Strategy 1 **Strategy 2** **Strategy 3**

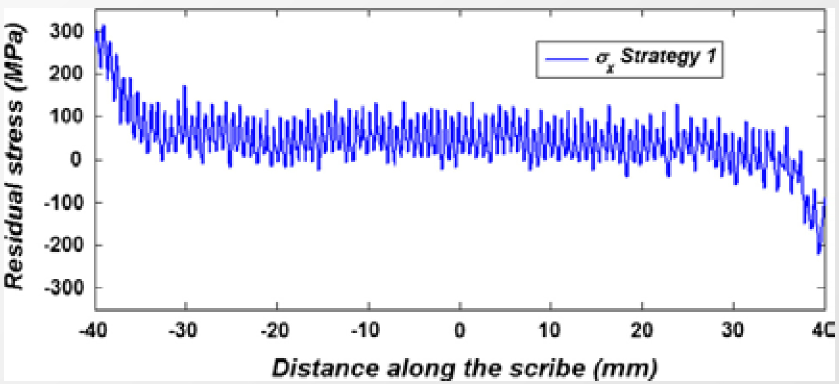


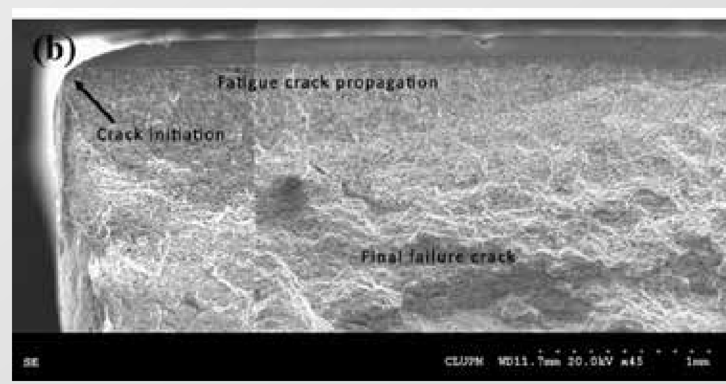
FATIGUE LIFE ENHANCEMENT OF NOTCHED AL2024-T351 SPECIMENS

LSP Treatment Strategy 1



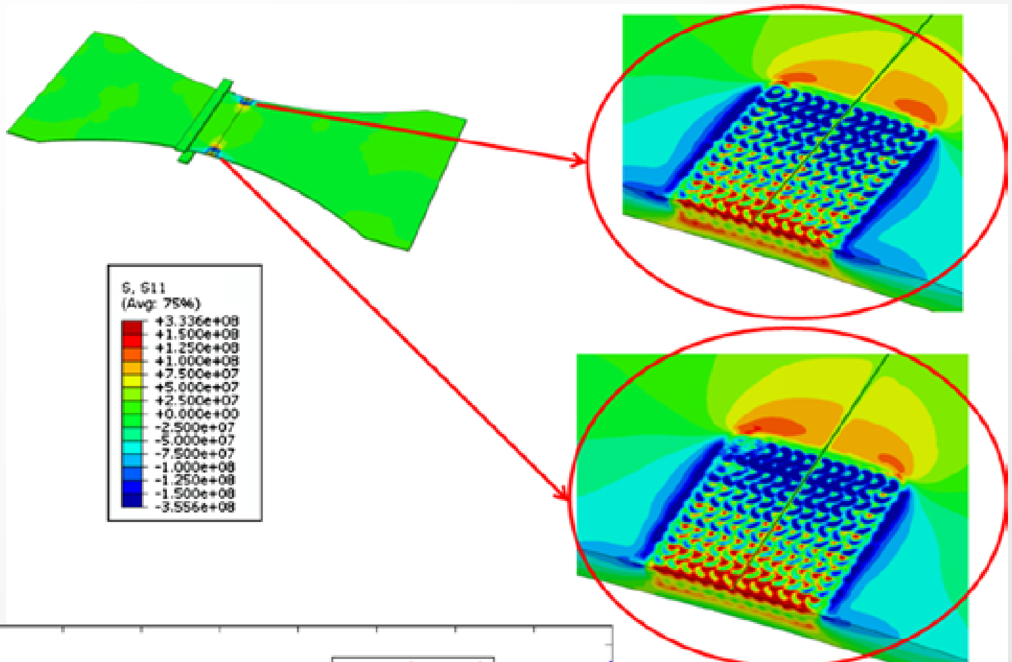


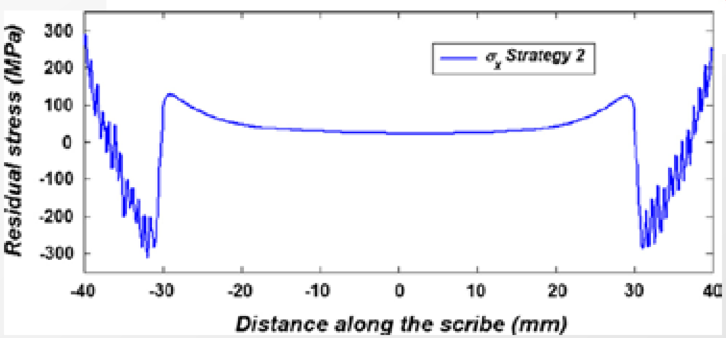


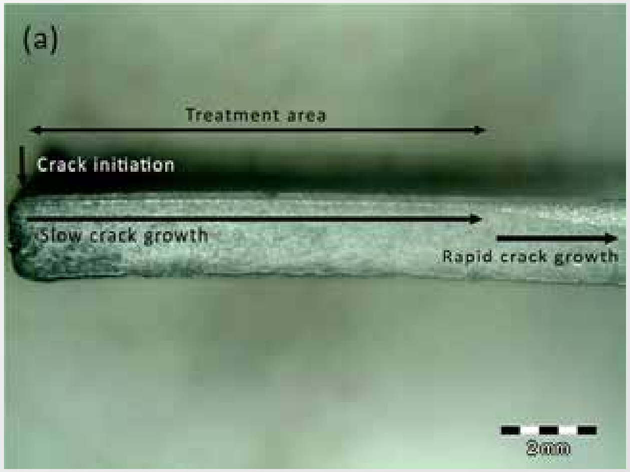


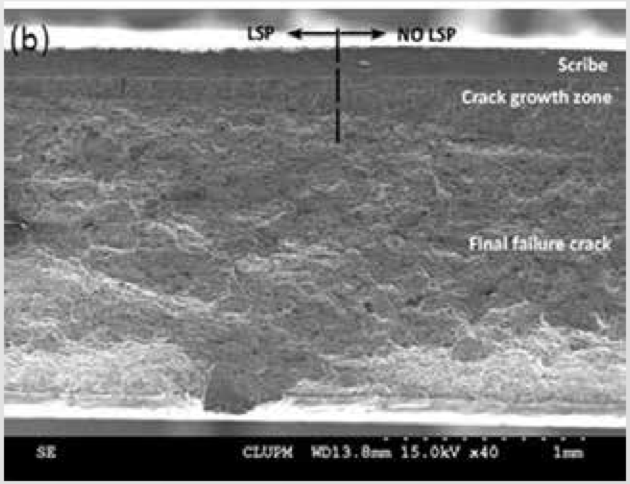
FATIGUE LIFE ENHANCEMENT OF NOTCHED AL2024-T351 SPECIMENS

LSP Treatment Strategy 2

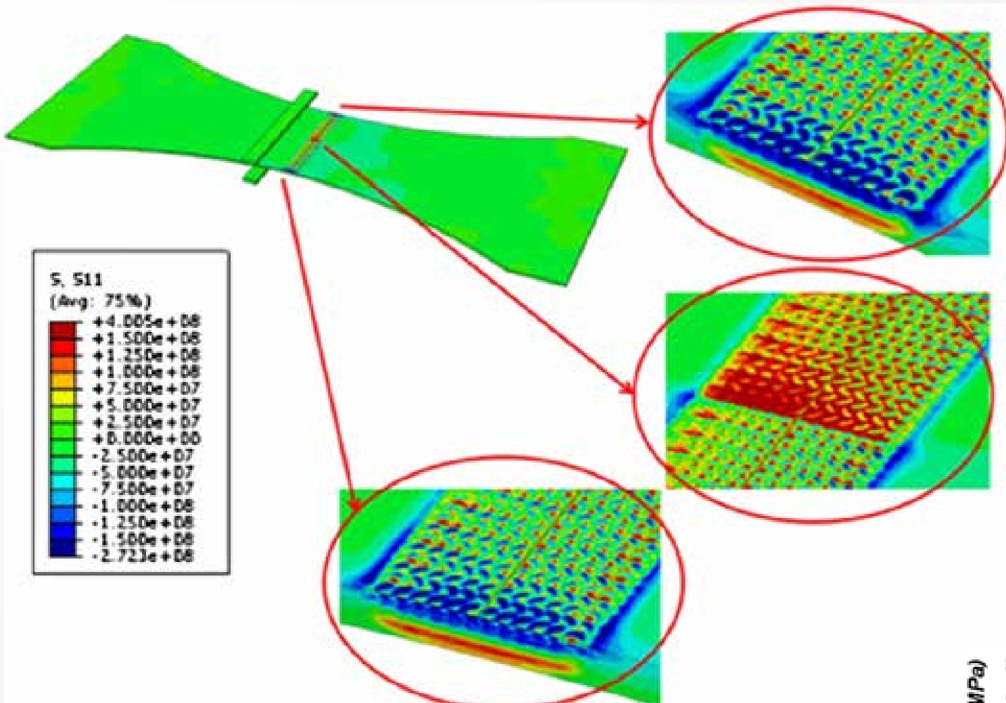


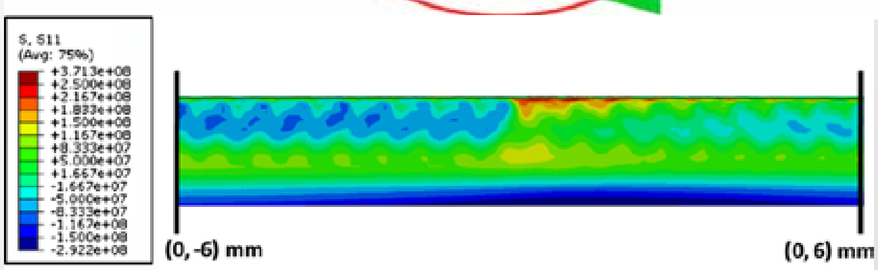


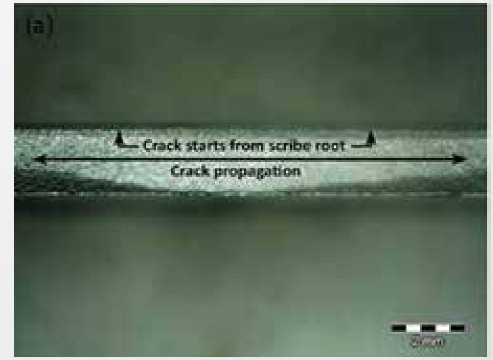


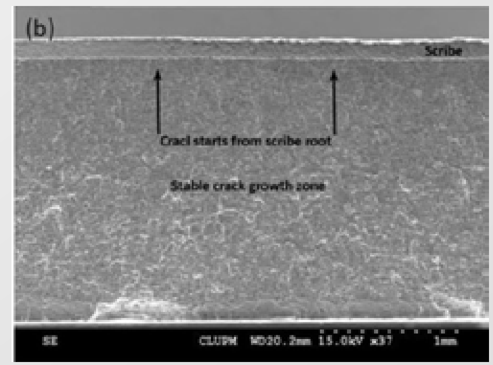


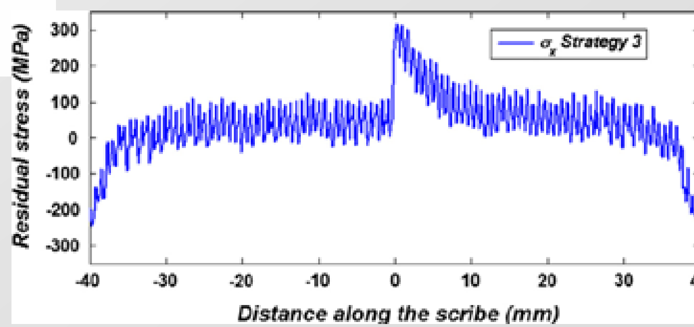
LSP Treatment Strategy 3



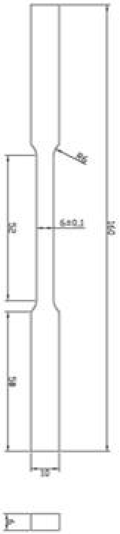




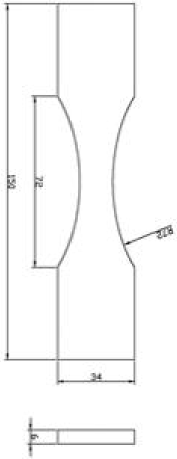




EXPERIMENTAL RESULTS



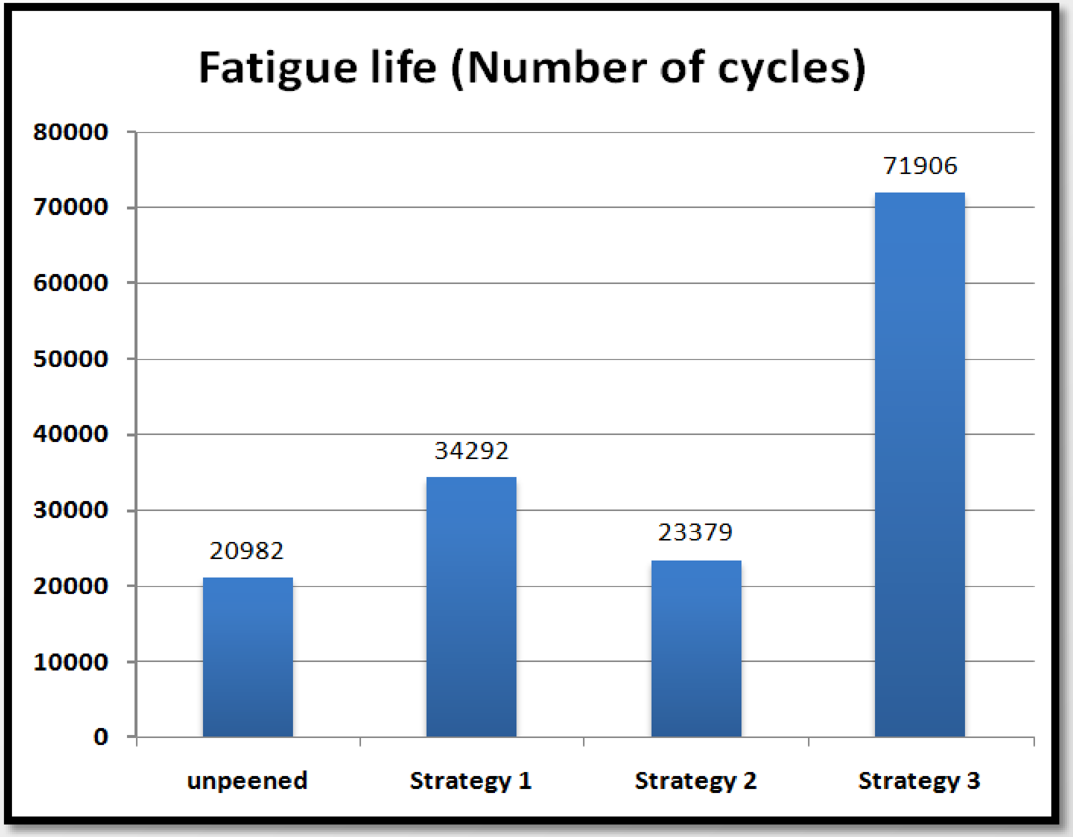
“Sub-size” Tensile Specimen
ASTM E 8M



“Bone” Fatigue Specimen
ASTM E 466

EXPERIMENTAL RESULTS

Fatigue Life enhancement of notched Al2024-T351 specimens

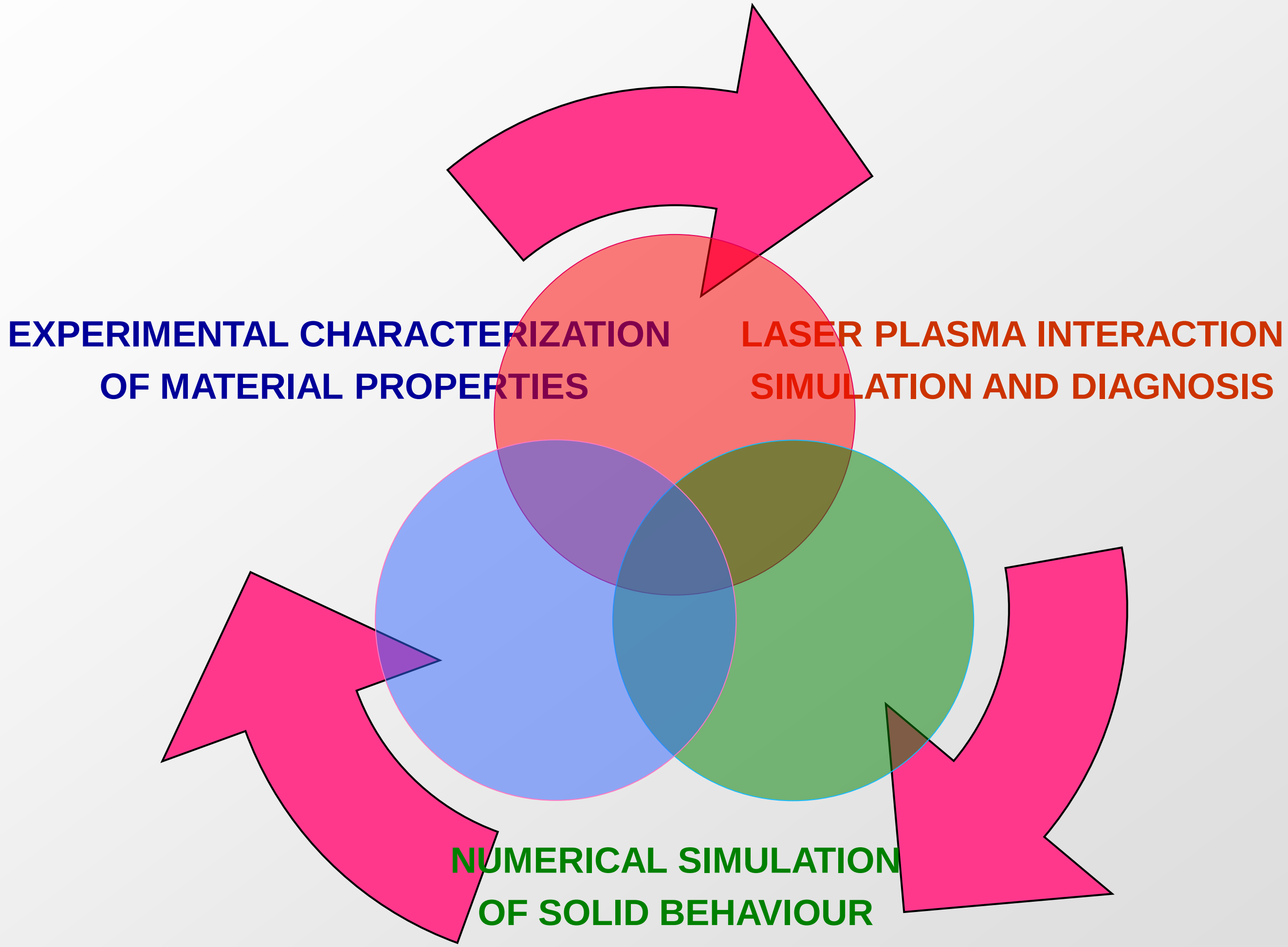


C. CORREA et al.: International Journal of Fatigue, 70, 196–204 (2015)

DISCUSSION AND OUTLOOK

- **The need for a practical capability of LSP process control in practical applications has led to the development of comprehensive theoretical/computational models for the predictive assessment of the complex phenomenology involved.**
- **The developed calculational model (SHOCKLAS) allows a systematic study of LSP processes starting from laser-plasma interaction. The integrated laser-plasma analysis routine provides a unique capability for process parametrization.**
- **The beneficial effect of LSP treatments on the fatigue life enhancement of different materials has been experimentally demonstrated with full coincidence against numerical predictions, what directly allows the appropriate engineering of RSs fields in view of mechanical and fatigue life improvement.**
- **Concretely, the possibility of inducing through-thickness RS's fields in thin Al2024-T351 plates with minor degree of local+global deformation (as required for improved fatigue life) has been both theoretical and experimentally demonstrated by the authors.**
- **The predictive assessment capability for LSP treatments developed at CLUPM has been proven to be a very convenient design tool for the treatments strategy optimization regarding RS's fields and resulting fatigue life enhancement.**
- **The CLUPM coupled Modelling/Experiment/Testing approach for the development of LSP treatments has revealed itself as a key tool for process understanding and practical transfer to industry.**

The UPM Laser Centre Approach to LSP Development



ACKNOWLEDGEMENTS

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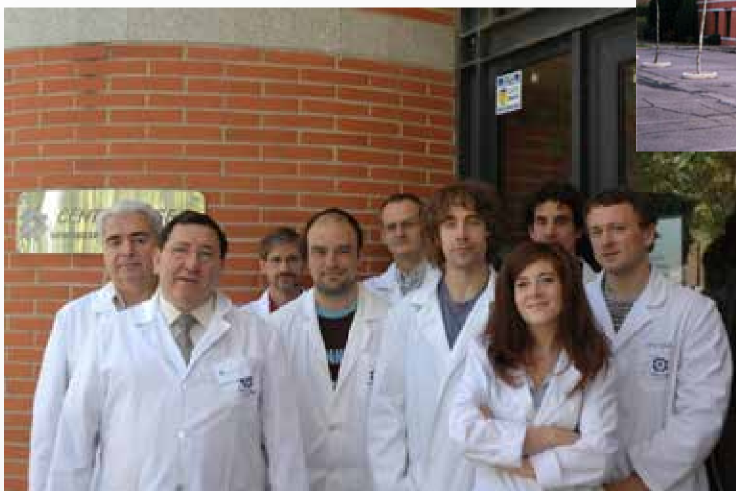
The LSP Team at UPM Laser Centre



Thank you very much for your attention !

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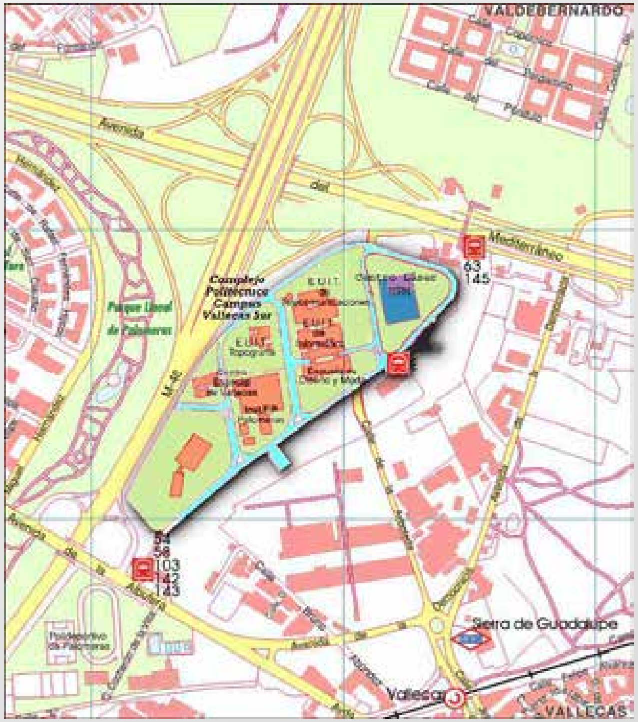
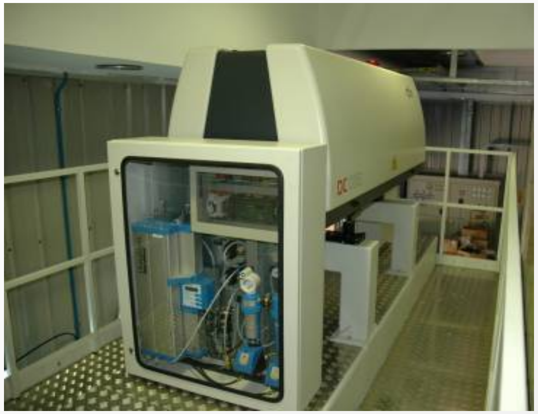


Major Facilities (1/4)



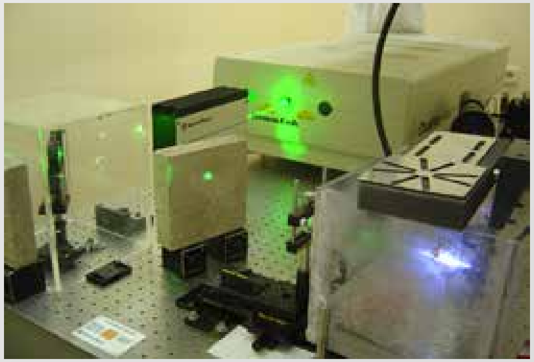
Major Facilities (2/4)








Major Facilities (3/4)



Major Facilities (4/4)